DEVELOPMENT OF A PAVEMENT LIFE CYCLE ASSESSMENT TOOL UTILIZING REGIONAL DATA AND INTRODUCING AN ASPHALT BINDER MODEL

BY

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THESIS

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Abstract

The ability to evaluate the sustainability of roadway and pavement systems has become an important and emerging topic in the field of transportation engineering. Life cycle assessment (LCA) is a quantitative method that can be used to measure the environmental impacts of pavements. A LCA framework for pavements is developed to evaluate the environmental burdens of five phases in the life cycle: material production, construction, maintenance, use, and end-of-life. The framework is incorporated into a user-friendly software tool that can be used to facilitate LCA for pavements. As a data-driven methodology, LCA is highly dependent on the data quality and appropriateness of its life cycle inventory. Therefore, a regional inventory database of major material production and construction processes related to pavements is compiled to reflect the State of Illinois, the relevant region in this study. Asphalt binder is one of the major materials contributing to the environmental impact of asphalt pavements. Therefore, in order to improve the accuracy of the inventory, life cycle models for the production of asphalt binder are also developed for five regions in the United States. Findings indicate that the variation in energy consumption and global warming potential (GWP) from binder production can be as high as 24% and 41%, respectively. To validate the LCA framework, a case study regarding a flexible pavement is analyzed for a 60-year period that covers all five phases of the life cycle. With regards to energy and GWP, respectively, the use phase contributes the highest (91.5%, 92.3%), followed by the material phase (3.9%, 3.4%), maintenance phase (3.2%, 2.9%), construction phase (1.2%, 1.2%), and finally the end-of-life phase (0.3%, 0.3%). Sensitivity analyses are also performed to consider different asphalt binder models and landfilling scenarios.

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List of Acronyms and Abbreviations

asPECT	Asphalt Pavement Embodied Carbon Tool
Athena	Athena Sustainable Materials Institute
CONCAWE	Conservation of Clean Air and Water in Europe
CRCP	Continuously Reinforced Concrete Pavement
DOT	Department of Transportation
ECC	Engineered Cementitious Composites
eGRID	Emissions & Generation Resource Integrated Database
EIA	(U.S.) Energy Information Administration
EPA	(U.S.) Environmental Protection Agency
Eurobitume	European Bitumen Association
FHWA	Federal Highway Administration
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GTR	Ground Tire Rubber
GWP	Global Warming Potential
HHV	Higher Heating Value
IEA	International Energy Agency
IRI	International Roughness Index
ISO	International Standards Organization
ISTHA	Illinois State Toll Highway Authority (also Illinois Tollway)
JPCP	Jointed Plain Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LOR	Level of Regionalization
MOVES	Motor Vehicle Emission Simulator
NEB	(Canadian) National Energy Board
NETL	(U.S.) National Energy Technology Laboratory
PADD	Petroleum Administration for Defense Districts
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCA	Portland Cement Association
PE-2	Project Emissions Estimator
PLCA	Pavement LCA
PMB	Polymer-Modified Binder
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles
SBR	Styrene Butadiene Rubber
SBS	Styrene Butadiene Styrene
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
U.S.	United States
US-EI 2.2	U.S.-Ecoinvent Database Version 2.2
WTT	Well-To-Tank
WTW	Well-To-Wheel

1 Introduction

Transportation infrastructure is an important social and economic component of any nation's well-being, and it must be adequately maintained as the demand for mobility continues to increase. The International Energy Agency (IEA) has predicted that in 2050 global travel will double the demand in 2010 to reach nearly 115 trillion annual passenger- and freight-tonne-kilometers (Dulac, 2013). Countries, such as the United States (U.S.), are spending massive amounts of money in the transportation sector. The U.S. Federal Highway Administration (FHWA) reported nearly $150 billion in federal, state, and local highway expenditures in 2010 (U.S. DOT, 2013). However, the transportation sector not only has a significant social and economic impact, but also a large environmental impact. The IEA has estimated that almost 25% of global CO_2 emissions can be attributed to the transportation sector (Cazzola et al., 2009). Thus, in order to be sustainable for future generations, transportation infrastructure today must be planned with regard to all three of these components – social, economic, and environmental.

A large portion of transportation infrastructure includes the construction and maintenance of roadways. In the U.S., the National Highway System encompasses a network of more than 223,000 miles needed to support approximately 1 trillion annual vehicle-miles (FHWA, 2012). FHWA, along with other State Departments of Transportation (DOT) and private roadway agencies, is undertaking various efforts to ensure the sustainability of road pavements in their jurisdiction. Some of these initiatives include incorporating and increasing the use of recycled materials (e.g. recycled asphalt shingles, fly ash, steel slag), using innovative production and construction techniques that are more efficient and less energy intensive (e.g. warm-mix asphalt, two-lift paving), and finally evaluating sustainability using both qualitative and quantitative assessments (e.g. sustainability rating systems, life cycle assessment). The last initiative of evaluating the sustainability of pavements is the focus of this thesis. Environmental assessment is an important component when considering the sustainability of roadways because it can more systematically identify sustainable practices and thus provide inform sustainable decisions.

1.1 Background

Environmental assessment can be roughly divided into two categories: qualitative and quantitative systems. Regarding pavements, qualitative approaches take the form of sustainable rating systems (SRS), while quantitative approaches use life cycle assessment (LCA).

1.1.1 Introduction to Sustainable Rating Systems

Ratings systems ranks projects depending on the amount of points fulfilled from a list of criteria. These criteria can be qualitative or quantitative, and thus subjective or objective. In addition, they can be used to evaluate a transportation system at a project-level, a network-level or an agency-level. The globally recognized Leadership in Energy and Environmental Design (LEED) program is an example of a SRS for buildings. FHWA recently released a transportation-related rating system in 2012 called Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), while other entities have developed tools such as Greenroads (private), Envision^{TM} (American Society of Civil Engineers), I-LAST (Illinois Department of Transportation), and GreenPave (Ontario Ministry of Transportation). Rating systems do not provide any physical values associated with sustainability, but rather given an overall relative rating of the project (e.g. Platinum, Gold, Silver, Certified).

1.1.2 Introduction to Life Cycle Assessment

Life cycle assessment is another type of environmental assessment that evaluates the entire life cycle of a system in order to give numerical results characterizing the system's environmental impacts. For example, in a pavement system, five life cycle phases are often considered (Santero, 2009). These include the material acquisition and production phase, the construction phase, the maintenance phase, the use phase, and the end-of-life (EOL) phase. Generally, there are two main types of LCA: input-output (IO) and process-based. A hybrid LCA combines the two methods, using the former method for upstream processes and the latter method for major system processes.

The IO-LCA approach aggregates all of the input processes of the system and outputs the system's total environmental impacts. Each of the input processes records its own environmental burdens, in addition to the amount needed from each of the other processes and their environmental burdens and so on to generate a unit of the original process. The recursive nature of this method allows for a complete evaluation of the system. An environmental IO-LCA tool (EIO-LCA) that uses the U.S. economic sectors as input processes has been developed by Carnegie Mellon University (2008). In general, the IO-LCA method is fairly quick and easy to use, but does not allow for flexibility or customization.

The process-based LCA looks at the material and energy inputs and environmental outputs to each process in the life cycle of the system. This includes processes related to the manufacturing, assembling, maintaining, using, and disposing of the product. As opposed to the IO-LCA, the process-based LCA is individualized for every product system, making it a more nuanced, but also very tedious and data-intensive method. The process-based approach is used in this thesis.

1.1.3 Guidelines to Life Cycle Assessment

A methodological framework is given in International Organization for Standardization (ISO) 14040 that suggests four steps to conducting LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation (1997). These four steps are followed in this study and illustrated in Figure 1.1.

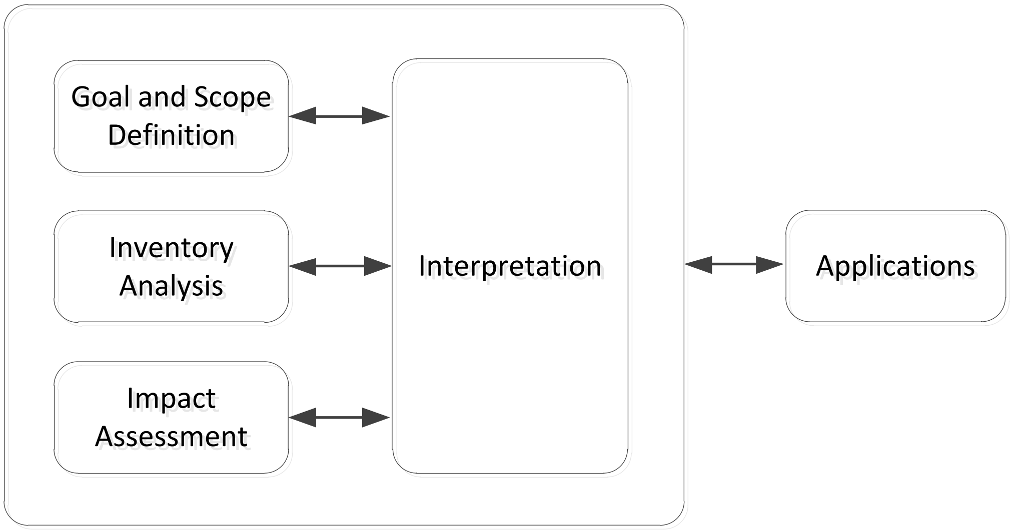

Figure 1.1 Procedure flow for conducting a LCA (from ISO 14040).

The first component to any LCA is the goal and scope definition. The goal includes detailing the reasons for conducting the study as well as specifying the intended application and audience. Describing the scope of the study is critical, as it enumerates the major assumptions, boundaries, requirements, and definitions considered in the study. Some major items to be discussed in the scope definition include functional unit, product system, system boundaries, impacts categories, and data quality and collection.

The second component of the LCA is the inventory analysis, which involves both data collection and analysis. As the process-based LCA is largely dependent on the quality of the data, this step can be very time-consuming and tedious. Inventory data collection is conducted based on the goal and scope of the intended LCA and application. In addition, the life cycle inventory (LCI) database must be sufficiently transparent to include descriptions of allocation procedures and system boundaries for individual unit processes.

Impact assessment is the third component of the LCA. The LCI analyzed in the previous step is now characterized using published impact assessment methods. The LCI data are associated with specific environmental impacts (classification) and assigned a unit contribution to each relevant environmental impact (characterization). After the required LCI data are classified, characterized, and summed for each impact category, the various impacts categories themselves can then be normalized against each other and given a weighting to provide a single environmental score for the system.

The fourth and last component is interpretation. The inventory analysis and impact assessment are evaluated against the original objectives and parameters stated in the goal and scope. Appropriate conclusions and recommendations can be made from the findings based on the goal and scope. As seen in Figure 1.1, the LCA method is not a linear process, but rather, it is an iterative process that can be continually improved after the LCA output is interpreted. For example, if the inventory analysis and impact assessment are not consistent with the goal and scope, the inventory can be improved with more focus on high impact items or the assessment method can be reassessed for inadequacies.

1.2 Problem Statement

Various pavement studies have applied LCA with both region-specific and generic data, but there does not exist an appropriate database of major processes that would be suitable for assessing pavement systems in the U.S., much less the Midwest region that is the focus of this thesis. In particular, there does not exist LCI models for the production of asphalt binder, arguably the most environmentally impactful material in flexible pavements that account for the wide regional variability in the U.S. Existing studies have used databases for asphalt binder developed mostly outside the U.S. (i.e. in Europe and Canada) to fulfill this gap. In addition, there are common limitations to existing pavement LCA studies, which include omitting sequences in the life cycle (e.g. the use and end-of-life phases) and reporting a limited set of impacts (e.g. only global warming potential) or only inventory results (e.g. energy consumption and CO_2 emissions). A full pavement LCA requires that the entire life cycle to be evaluated and that impact assessment be performed.

1.2.1 Research Objectives

The major objectives of this study are tri-fold:

1. To describe a conceptual pavement LCA framework and a software pavement LCA framework for U.S. Midwest region that cover all five phases of the pavement life cycle;
2. To investigate the variability in environmental impacts related to asphalt binder production by developing regionalized LCI models for asphalt binder production that consider differences in processes used in five U.S. regions; and
3. To conduct a full pavement LCA case study using a regionalized inventory database and a regionalized LCA framework to assess an Illinois highway project.

1.2.2 Impact of the Study

It is anticipated that this study will add to the growing literature and resources regarding the framework development and implementation of pavement LCA. The LCA tool developed as part of this thesis can be used by highway agencies to calculate the environmental impacts of future pavement projects and existing designs to allow for a systematic sustainability assessment of current practices and technologies. The regionalized LCI models for asphalt binder developed will fill an important gap in the U.S. for pavement

LCA applications. The LCA framework described in this study can also be further improved, adapted, and expanded to form a more complete procedure and a tool that practitioners can use to conduct pavement assessment.

Ultimately, this study aims to emphasize the importance of considering the entire pavement life cycle, using relevant inventory data, and applying appropriate assumptions when conducting LCA for pavement systems. The procedures, models, and tool developed in this study can be used to evaluate the environmental burdens of past and present pavement practices, guide practitioners in the design and construction of future sustainable pavements, and communicate quantifiable improvements in sustainable pavement practices to the public. With access to a practical and appropriate method of implementing LCA, the pavement industry can work to reduce the environmental impacts from their sector, often coinciding with an economically and environmentally favorable reduction in energy and fuel consumption.

1.2.3 Scope of the Study

The first chapter of this thesis provides an overview of current literature related to pavement LCA as well as literature relevant to the development of LCI models for asphalt binder production. The second chapter describes the pavement LCA framework and software design. The major assumptions and boundaries of each of the five life cycle phases are addressed. The third chapter presents a framework for determining the environmental inventory and impacts for asphalt binder production. Supporting methodologies and data sources needed to develop regionalized LCI models are presented in detail. The fourth chapter discusses a case study involving a reconstruction project using flexible pavement. The entire life cycle assessment is performed and alternative scenarios are discussed. The thesis concludes with the fifth and final chapter, summarizing critical findings of the study and offering recommendations for future work.

2 Literature Review

This chapter summarizes major literature regarding LCA as applied to pavements and gives an overview of LCI studies pertaining to the production of petroleum products, focusing on asphalt binder.

2.1 Life Cycle Assessment for Pavements

The literature surrounding pavement LCA is discussed in two parts. First, a review of existing life cycle inventories for pavement materials and processes is given. These LCIs are important because they must ultimately be used in pavement assessments. Second, a chronological timeline of major pavement LCA literature including case studies, frameworks, and tools is provided.

2.1.1 Life Cycle Inventory

Inventory analysis is a crucial step of the LCA as it requires tedious data collection when using the process-based LCA approach. Various standalone LCIs for the major materials needed in pavement construction have been published. Four commonly-cited studies have been selected for discussion. For asphaltic materials, studies by Athena Sustainable Materials Institute (Athena) for North America and the European Bitumen Association (Eurobitume) are often referenced (Athena, 2001; Blomberg et al., 2011, respectively). For Portland cement materials, LCI data is often used from studies by Athena (2005) for Canada and the Portland Cement Association (PCA) for the U.S (Marceau et al., 2006, 2007).

The LCI studies mentioned incorporated different alternatives in their modeling to allow for more representative inventories. Two of the reports, both from Athena, considered regional variance. Athena's LCI for asphalt binder considered both U.S. and Canadian scenarios for crude oil transportation, while the LCI for Portland cement and Portland cement concrete (PCC) reported data from four Canadian regions. In addition, both of the PCC reports from Athena and PCA considered different strengths and applications of concrete. Eurobitume's LCI also considered different asphalt materials, including straight binder, polymer-modified binder, and emulsion. All of these studies use a combination of collected local data, publicly available sources, and commercial LCI databases.

It should be noted that the four material LCIs described only dealt with the production of the materials, and not construction or disposal. A number of studies have been performed to assess the change in environmental burden that may result from using alternative materials or processes. For example, a study by Hassan (2010) investigated both the economic and environmental impacts of using warm-mix versus hot-mix asphalt in a project. In addition, Bartolozzi et al. (2011) quantified the effect of using rubberized asphalt binder as an alternative to conventional binder in another study.

In addition to material-focused LCIs, some studies have compiled complete inventories needed to assess an entire road project. These analyses are not technically considered full LCA studies because they do not include impact characterization and assessment. However, in this review, these partial LCA studies are discussed along with full LCA studies in the next section.

2.1.2 Life Cycle Assessment Models and Tools

There are already a few detailed summaries of existing pavement LCA literature that have been published exclusively (Santero et al., 2011a, 2011b) or as a component of a thesis (Kang, 2013; Santero, 2009). The most comprehensive review was released in two parts by Santero et al. (2011a, 2011b), summarizing existing pavement LCA studies, frameworks, and major research gaps. Most of the gaps described pertain to the use phase of the life cycle, dealing with complex topics such as rolling resistance, albedo, PCC carbonation, lighting, and leachate. Topics such as traffic delay, landfilling, and recycling are also included. The remainder of this section gives a chronological sampling of some key pavement LCA literature as well as the general historical trend of research in this field.

The first studies to be discussed are two of the earliest pavement LCA studies using the process-based LCA approach. The first study was published by Häkkinen and Mäkelä (1996). Often considered the pioneering work of its kind, Häkkinen and Mäkelä conducted a complete LCA for both PCC and asphalt pavements, including all life cycle phases and impact assessment. The study was based on both literature values and data collected from Finish companies in the early 1990s. The use phase included lighting, traffic disturbance from construction and maintenance, carbonation, and general traffic. The study found that general traffic, with fuel consumption estimated and considered equal regardless of pavement type, had the greatest environmental impact, followed by lighting. The second study was released by Stripple (2001) and focused largely on compiling a comprehensive inventory. Data were collected for both material and construction processes, specific to the Swedish context. The entire life cycle was analyzed without impact assessment, and the use phase marginally considered traffic, as the inventory collection was the focus of the report. The inventory in this second study has been used by numerous subsequent LCAs (e.g. Wang et al. (2012), Yu and Lu (2012), Zapata and Gambatese (2005)). Thus, the first study by Häkkinen and Mäkelä presented pavement LCA performed over the entire life cycle with impact assessment, while the second study by Stripple contributed to the development of a regional, comprehensive inventory.

The next three selected studies continued to contribute to different aspects of the then-emerging pavement LCA literature. A study in 2004 by Treloar et al. (2004) considered the vehicle life cycle as well as the roadway life cycle. A hybrid LCA approach was used, and the input-output method was used to obtain inventory concerning vehicle manufacture, repair, and use in the Australian context. In 2005, Zapata and Gambatese used a mixture of LCI literature sources, complemented with a few contractor surveys to compare the production and construction of PCC and asphalt pavements. While, the aforementioned three studies had collected or modeled their own LCI data, Zapata and Gambatese and later studies tended to use a combination of existing and newly collected LCI data, often leading to an inventory of varying spatial and temporal characteristics. An exception to this trend is a study released by Athena in 2006 that evaluated energy consumption and GHG emissions from the production and construction of Canadian roadways (Meil, 2006). A regionalized LCI database was used, allowing for separate analyses to be performed for two provinces in Canada. Recycled asphalt pavement (RAP) was considered in this study.

In 2004 and 2005, two of the first pavement LCA tools were released. The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is an open-source spreadsheet tool that covers the entire life cycle except for the use phase (Horvath, 2003). First released in 2004 by the University of California, Berkeley, the tool followed a hybrid LCA approach by supplementing primary and literature data with economic IO-LCA. This tool is no longer updated and was superseded by a web-based tool Roadprint Online in 2012 (Lin & Muench, 2012). In 2005, Birgisdóttir described an LCA model called ROAD-RES, which can assess leaching impacts of waste residues in road construction. The LCI included data from Danish contractors and producers as well as European literature sources.

In 2008 and 2010, two studies were released that follow the trend toward developing LCA tools and placing more emphasis on the use phase. These studies coincided also with the papers by Santero et al. (2011a, 2011b) and the Pavement LCA Workshop hosted at the University of Davis in 2010 that released a concept LCA framework for pavement (Harvey et al., 2010). In 2008, Huang et al. (2009) described a spreadsheet-based framework for a pavement LCA tool, excluding the use and EOL phases. A case study was also investigated, that involved using recycled waste glass and RAP. In 2010, Zhang et al. (2010) detailed an LCA model for pavement overlay systems that covered the entire life cycle, with special care to traffic delay, roughness, and the use of engineered cementitious composites (ECC) in PCC. Each of the three pavement types considered (asphalt, PCC, and PCC with ECC) were given different distress indexes over time based on their maintenance schedules and predicted deterioration[1].

Current studies in pavement LCA have also continued to further develop LCA tools and the pavement use phase. The asphalt Pavement Embodied Carbon Tool (asPECT) tool was first released in 2010 to calculate the carbon footprint of asphalt pavements (TRL, 2010). The asPECT tool calculated GHG

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[1] Deterioration was predicted based on Michigan DOT’s pavement design manual

emissions for all phases of the life cycle, specifically dealing with asphaltic material processes and thus omitting the use phase. In 2012, Mukherjee and Cass (2012) developed a web-based tool called Project Emissions Estimator (PE-2) to implement the LCA model described in a paper the year before (Cass & Mukherjee, 2011). The LCA model was based on data collected from 14 Michigan DOT projects as well as literature and commercial sources. Traffic delay is included in the framework, and the tool is intended to be used for project benchmarking and prediction of GHG emissions.

In 2012, Yu and Lu (2012) focused on the use phase, specifically rolling resistance, albedo, and carbonation, as well as traffic congestion and recycling in the EOL phase for pavement overlays. Various existing software and LCI data were compiled and used to conduct an LCA of the entire life cycle. In addition, Wang et al. (2012) specifically focused on the issue of rolling resistance for various traffic volumes, rehabilitation qualities, and pavement types. Existing literature and commercial LCI data were disaggregated and modified to better represent the California region, and a sensitivity analysis was done to assess the importance of using regionalized data. A similar regionalization of LCI data was also performed by Kang et al. (2014) for the Illinois region.

In 2013, Athena released the Athena Impact Estimator for Highways software, which is currently the most developed and accessible pavement LCA tool (Athena, 2013). The entire life cycle is accounted for, including impacts from fuel consumption in the use phase due to stiffness and roughness of the pavement surface layer. The inventory is proprietary and includes collected data relevant to the North American region. Lastly, in the same year, a thesis by Santisteve (2013) developed a framework for assessing the noise impacts of road transportation – a commonly neglected area in pavement LCA.

Overall, the trajectory of pavement LCA research has varied since the field emerged in the 1990s. Early studies began with a rough but complete life cycle assessment and focused on developing usable, comprehensive inventories. Case studies emerged that incorporated specific interests (e.g. recycled materials, overlays, vehicles), using inventory data from existing sources. More recently, studies have moved towards developing more accessible tools to perform LCAs for a wide range of projects, rather than isolated case studies. Recently, more research has been focused on developing the use phase as well as compiling more relevant and regionalized LCI data.

2.2 Life Cycle Models Relevant to Asphalt Binder

An important component of any LCA is the quality of the inventory data. In pavement LCA, this is especially important for heavily contributing materials, one of which is asphalt binder. In this section, studies relevant to the life cycle modeling of asphalt binder are discussed. As asphalt binder is a petroleum-derived product, the first subsection addresses general life cycle models for petroleum products while the second subsection addresses LCIs specifically for asphalt binder.

2.2.1 Life Cycle Models for Petroleum Products

A number of life cycle models and assessments have been developed for petroleum products, especially for transportation fuels such as gasoline, diesel, and jet fuel. In this section, a survey of various published reports related to life cycle models for petroleum products is presented, followed by a discussion of the Greenhouse Gases Regulated Emissions and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory. The methodologies used in these life cycle models are highly applicable to developing a model for the production of asphalt binder, which is a petroleum product.

2.2.1.1 Selected published reports

The literature reviewed in this subsection includes three comprehensive life cycle models developed for transportation fuels. The scopes of these models included crude extraction to refining to consumer (well-to-tank, WTT) and often extended to also include fuel consumption in vehicles (well-to-wheels, WTW). A variety of sources were used to compile the inventories, including open source governmental data, proprietary company data, literature sources, and optimization programs for refineries.

The first study was released by the U.S. National Energy Technology Laboratory (NETL) in 2008 (Skone & Gerdes, 2008). The purpose of this study was to provide a 2005 U.S. average GHG baseline for conventional petroleum-based transportation fuels to be used for comparison against alternative transportation fuels (e.g. coal, biomass). The study specifically looked at conventional gasoline, conventional diesel fuel, and kerosene-based jet fuel, and reported the baseline WTT GHGs to be 19.6, 18.4, and 15.5 kg CO_2E/mmBtu[2], respectively. The data are representative of the year 2005 and reportedly accounts for 99% of mass, energy, and environmental relevance. Publically available data was used for all inventory data except crude oil extraction data purchased from the GaBi 4 database. A follow-up NETL study was published in 2009 that investigated the effect of crude source, crude transportation, and refining (Gerdes & Skone, 2009). The range of WTT GHG emissions for gasoline when considering various crude sources ranged from 15.5–35.6 kg CO_2E/mmBtu, as compared to the baseline value of 19.6 kg CO_2E/mmBtu.

The second study was published in 2009 by Life Cycle Associates, LLC for New Fuels Alliance, a group based in the U.S (Unnash et al., 2009). This study is unique in that it assessed both the direct and indirect

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[2] Lower heating value

GHG emissions associated with petroleum fuels. The indirect emissions are a result of various effects of petroleum production such as the protection of oil supply, land use change, and the production of other refinery co-products. The study used the GREET model as a basis for the assessment and compared the generic values and assumptions from GREET to those reported in published studies and data sources. Specifically discussed are emissions associated with unconventional petroleum resources not considered in GREET, emphasizing the variability in calculating the impacts of petroleum fuel production. No primary survey or inventory was directly collected. The WTT GHG results for various petroleum supply options (conventional, U.S. offshore, Iraqi, Canadian oil sands, Venezuelan heavy, Nigerian, California thermally enhanced) range from 22.1–45.9 kg CO_2E/mmBtu of gasoline.

The third study was released by Jacobs Consultancy Inc. for the Alberta Energy Research Institute in 2009 (Keesom et al., 2009). This study focused on comparing GHG emissions between North American crudes and other imported crudes. The GREET model was used as a base for the study, but was supplemented by rigorous crude production and refining models based on relevant physical material properties and processes. An emphasis was placed on the upgrading and refining processes needed for Canadian oil sands. The reported WTT GHG emissions range from 25.6–41.9 kg CO_2E/mmBtu of gasoline and up to 47.3 kg CO_2E/mmBtu with bitumen upgrading.

2.2.1.2 The Greenhouse Gases Regulated Emissions and Energy Use in Transportation model

The GREET model was first released by the U.S. Argonne National Laboratory in 1996 and has since undergone various revisions, with the latest version being released in October 2013. The GREET model is implemented in a spreadsheet that can be used to estimate the energy and emissions associated with transportation fuels, including non-petroleum fuels. The newest version GREET 1 2013 reports 9 emissions (CO_2, CH_4, N_2O, VOC, SO_X, CO, NO_X, PM_{10}, $PM_{2.5}$) and includes 9 fuel pathways[3], including one for petroleum fuels (Wang, 1999a). Numerous processes make up each pathway, and each of these processes have resource inputs or technology (i.e. combustion or chemical reaction) outputs. Assumptions and concepts used in early versions of the GREET model were influenced heavily by (Delucchi, 1993b) and have been documented extensively (Wang, 1999a, 1999b). Many of these data are still utilized in the current version, and updated documentation is available (Delucchi, 2003).

The GREET model calculates energy consumption based on a process-to-primary energy ratio that is based on the energy efficiency. For example, crude oil extraction is assumed to have a 98% recovery

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[3] Petroleum fuel, natural gas fuel, coal fuel, fossil fuel, renewable, biomass, nuclear, non-fossil fuel, renewable natural gas

efficiency, which means that 1 mmBtu of fuel throughput requires (0.98^{-1}–1.00) mmBtu of energy. The percent shares of each type of fuel for each process is then applied to the appropriate combustion process and used to calculate the resulting energy consumption and emissions. This methodology requires iterative calculations for the processes.

In summary, the aforementioned studies and tools for assessing the life cycle impacts of petroleum fuels are very relevant for LCIs concerning asphalt binder production. The crude extraction and transportation processes are identical for all petroleum products. The refining process is more complex and requires differentiation among petroleum products. However, generic petroleum product studies can be referenced to develop an allocation methodology appropriate for asphalt binder.

2.2.2 Life Cycle Inventories for Asphalt Binder

In addition to the life cycle models for fuel-related petroleum products, a few life cycle models have been developed specifically for asphalt binder. These include four LCIs from published reports by Häkkinen and Mäkelä (1996), Stripple (2001), Athena (2001), and Eurobitume (2011). In addition, commercial LCIs for asphalt binder production are available, including those from Ecoinvent. A review of these existing life cycle models now follow.

2.2.2.1 Häkkinen and Mäkelä (1996)

As part of a larger report assessing the environmental impact of concrete and asphalt pavements, Häkkinen and Mäkelä (1996) included the environmental burdens necessary for producing asphalt binder in Finland. A summary of the report is presented in Table 2.1.

Table 2.1 Summary of Binder Production Inventory from Häkkinen and Mäkelä

Published	1996, refining data from 1992
Region	Finland
System Boundaries	Crude production, crude transportation, refining
Data Sources	Plastic Waste Management Institute Data, collected data

Not many details are given regarding the life cycle model for asphalt binder production. The data is retrieved from one company and all calculations and assumptions are specific to Finland. It is unknown where the crude sources are from and how allocation is performed in the refining step. The system boundaries include precombustion or indirect fuel processes, but no processes beyond refining are considered. The study does note that the energy content of asphalt is taken to be 40 MJ/kg, but no further analysis is done with the feedstock energy.

2.2.2.2 Stripple (2001)

Similar to that in the previous report, the life cycle inventory for asphalt binder recorded in Stripple (2001) is part of a larger LCI study for pavements. A summary of the report is in Table 2.2.

Table 2.2 Summary of Binder Production Inventory from Stripple

Published	2001, with data from 1990 and 1995
Region	Sweden
System Boundaries	Crude production, crude transportation, refining, refined transport, storage
Data Sources	Swedish average electricity consumption, collected data

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. This implies that the allocation occurs at the refinery-level, but no further details are given. After refining, it is assumed that the asphalt binder is transported by tanker boat to a depot where it is stored for end-users. Round trip transportation is considered, where the return trip is empty and attributed to the binder life cycle. The study is not consistent in its treatment of pre-combustion fuel processes. The production of transportation fuels and generation of electricity is included, but the production of natural gas for crude extraction and heating oil for storage is not explicitly mentioned.

2.2.2.3 Athena Sustainable Materials Institute (2001)

A dedicated LCI report for roofing and road asphalt was released by Athena (2001). The crude production and refining data are based on U.S. processes, but both U.S. and Canadian estimates for crude transportation are given. A summary of the report is in Table 2.3.

Table 2.3 Summary of Binder Production Inventory from Athena

Published	2001, with data from 1990s
Region	U.S.
System Boundaries	Crude production, crude transportation, refining
Data Sources	Literature sources, Franklin Associates, SimaPro 5

The crude production is based solely on U.S. processes even though, for transportation purposes, it is assumed that 49% of crude has been imported from other countries. The refinery operations are examined at the process-level for energy allocation. The crude oil refined to asphalt binder undergoes four steps: desalting, atmospheric and vacuum distillation, and desaphalting. At each step, an allocation based on mass fraction is used to attribute the energy consumption. 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, and the system boundaries stop at the refining processes. The LCI from Athena contains the most comprehensive list of emissions when compared to the other reports included in this section.

2.2.2.4 European Bitumen Association (2011)

Eurobitume released a revised LCI report for asphalt binder production in 2011 that included data for straight asphalt binder as well as polymer-modified asphalt binder and asphalt emulsion (Blomberg et al., 2011). The report was developed following ISO 14040 and ISO 140444 standards, and an external review was conducted. In addition, this report utilized local questionnaires to collect regional information, resulting in a fairly comprehensive dataset representing between 20–68% of the production and refining processes in the desired region. In general, local sources of data were used when possible and data from Ecoinvent were supplementary. A summary of the report is given in Table 2.4.

Table 2.4 Summary of Binder Production Inventory from Eurobitume

Published	2011, with data from 2011
Region	Europe
System Boundaries	Crude production, crude transportation, refining, refined transport, blending, storage
Data Sources	Oil and Gas Producers, CONCAWE[4], collected local data, Ecoinvent 2.2

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. The fractions of crude throughput for asphalt binder production in the atmospheric distillation and vacuum distillation units are weighted using relative economic value. The allocation for the atmospheric distillation unit is 31%, while that for the vacuum distillation is 27%. The report suggests that other asphalt manufacturing processes (semi-blowing, deasphalting, and vis-breaking) contribute a negligible portion of the energy and emissions for asphalt binder production. The original study used mass allocation for crude extraction and economic allocation for refining, and a sensitivity analysis showed a greater environmental impact when only mass allocation is used. Finally, it is assumed that the refined material is transfer to the storage depot via pipeline and that various blending or milling processes are present, depending on the final binder product.

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[4] Conservation of Clean Air and Water in Europe

2.2.2.5 *Commercial Ecoinvent databases*

The Ecoinvent library includes a refinery process original called *Bitumen, at refinery/RER*, which represents approximately 5% of the asphalt binder production in Europe (Swiss Centre For Life Cycle Inventories, 2007). This LCI considers the most comprehensive life cycle for asphalt binder production, as it is part of a commercial database. Various literature sources and plant data are consulted for the inventory data, and the upstream processes are linked to other unit processes in Ecoinvent. The methodology used to model asphalt binder production is documented in Ecoinvent reports (Dones et al., 2007; Jungbluth et al., 2007). A summary of key information is given in Table 2.5.

Table 2.5 Summary of Binder Production Inventory from Ecoinvent

Published	2000, with data from 1990s
Region	Europe (with modified U.S. electricity if US-Ecoinvent is used)
System Boundaries	Crude production, crude transportation, refining
Data Sources	Literature, collected data

Even if the modified US-Ecoinvent process is used, it only differs from the original European process with respect to electricity generation, which has been re-routed to reflect the U.S. electricity grid. Thus, the crude sources are relevant to Europe and do not include crude extraction from North or South America. The refining processes are allocated at a process-level by mass, separate for energy from fuel and energy from electricity. The relative energy use for asphalt binder is 0.7, while in comparison, it is 1.0 for diesel and 1.8 for gasoline. The system boundaries stop at the refinery.

2.2.2.6 *Major challenges*

From the five LCIs examined, the major causes for discrepancies are time period, region, system boundaries, crude source distribution, and treatment of refinery allocation. The last two of these items are discussed further later in this section. A summary of these factors for each of the literature sources are given in Table 2.6. For these studies, the average energy and global warming potential (GWP) values given per tn.sh (short ton) of asphalt binder produced are 4174 MJ and 289 kg CO_2E, respectively. The standard deviations are 1178 MJ for energy and 132 kg CO_2E for GWP.

Table 2.6 Summary of Binder Production Studies

Author(s)	**Source**	**Region**	**System Boundaries**[5]					**Refining**		**Results per tn.sh**	
	Year		CP	CT	RF	RT	BS	allocation	level	kg CO_2E	MJ
Häkkinen, Mäkelä	1992	Finland	x	x	x			Unknown	---	299	5443
Stripple	1990s	Sweden	x	x	x	x	x	Mass	refinery	157	3298
Athena	1990s	Canada	x	x	x			Mass	process	477	4993
Eurobitume	2011	Europe	x	x	x	x	x	Economic	process	172	2627
Ecoinvent	1990s	Europe	x	x	x			Mass	process	340	4507

The sources of crude oil for refining are highly influential in the life cycle environmental impacts. In a study by NETL, it was found that well-to-tank GHG emissions for diesel fuel made from foreign crude oil was up to 59% higher than that from domestic crude oil (Gerdes & Skone, 2009). This is a result of the high environmental impact of transporting crude oil overseas as well as the different techniques used in extraction and the varying qualities of crude (i.e. heavy versus light) in other countries. From three of the LCI studies reviewed[6], the extraction and transportation process contribute between 30-65% and 10-25%, respectively, of the GWP emissions of the life cycle.

Another source of discrepancy between the LCI studies reviewed is the treatment of the refining processes. The refining of crude oil is a complex multiple output operation that involves many sub-processes and produces numerous co-products. Each refinery is different, depending on the type of crudes inputted and types of petroleum products outputted. To complicate the process, many of the fuels used in the refinery are co-products themselves. Various approaches have been used to allocate the energy and emissions from refining to specific products. The simplest method is to use a physical or non-physical parameter for allocation at the refinery-level. Physical parameters may include mass, volume or energy content, while an example of a non-physical parameter is economic or market value. This method has been used by existing studies (e.g. Aurangzeb et al. (2014), Stripple (2001)). To improve this basic approach, an allocation can be done at a process-level, where the energy and emissions at each available sub-process (e.g. atmospheric distilling, vacuum distilling) are allocated based on a physical or non-physical parameter. Various of this method have been used in a number of studies (e.g. Athena (2001), Blomberg et al. (2011), Skone & Gerdes (2009), Wang (1999a)). Furthermore, linear programming has also been used to allocate refinery operations (e.g. Tehrani (2007)). This is a more comprehensive approach that requires details on the performance of the plant processes.

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[5] CP = crude production, CT = crude transportation, RF = refining, RT = refined transportation, BS = blending and storage

[6] Stripple (2001), Eurobitume (2011), and Athena (2001).

Thus, there are a number of existing LCI studies that have been conducted for petroleum products, largely for transportation fuels and some for asphalt binder. Each study considers a different set of parameters, whether temporal, spatial or methodological. While Athena and US-Ecoinvent have released LCI data that most closely reflects the U.S. region, these studies are outdated and insufficient in representing the variation in production processes relevant to different regions in the U.S. An updated LCI model for asphalt binder is needed that can better reflect the set of crude oil sources and refining processes that are unique to major regions of the U.S.

3 Development of the LCA Framework and Tool

In this chapter, a description of the framework of the LCA tool is presented. This discussion includes the goal and scope definition for the LCA study, followed by a description of the software architecture of the LCA tool. Subsequently, the life cycle inventory and major assumptions for each of the five LCA stages in the pavement life cycle – material production, construction and maintenance, use, and EOL – are detailed.

3.1 Goal and Scope

The goal of this study is to carry out a complete assessment of the full life cycle of a pavement. A framework and software tool has been developed to facilitate the use of LCA to evaluate pavement projects. In addition, the study attempts to perform a regionalized LCA by using the most pertinent available data or models as well as appropriate assumptions corresponding to the region of interest.

This study is related to a project sponsored by the Illinois State Toll Highway Authority (ISTHA, henceforth referred to as the Illinois Tollway) that aims to develop a complete roadway/roadside LCA toolkit for the agency. The toolkit will contain modular LCA tools for each component of the roadway: pavement, structures, drainage, landscaping, and lighting. The project is a collaboration between the Illinois Tollway, the University of Illinois at Urbana-Champaign, Applied Research Associates, Inc., and theRightEnvironment, Inc. Nevertheless, the pavement LCA framework and tool developed in this thesis can be adapted and applied to various agencies and roadway networks.

The region of interest for this study is the State of Illinois, where the Illinois Tollway's network is located. Thus, the inventory data and assumptions used in this study reflect as closely as possible the actual processes and conditions in this region.

3.1.1 System Definition

The pavement system considered in this study does not consider any structures, drainage, landscaping or lighting. The pavement components include the unpaved and paved shoulders in addition to the mainline. The pavement structure includes the subgrade, subbase, base, and bound layers (i.e. binder course, surface or wearing course). Seal, tack, and prime coats are also considered. A diagram of the pavement components and structure is shown in Figure 3.1.

Figure 3.1 Pavement components and structure considered.

3.1.2 Functional Unit

The functional unit of a system provides a reference to which the results of the LCA study can be normalized (ISO, 2006). In this study, the functional unit is a one-directional highway segment capable of supporting urban volumes with a 60-year design period under the jurisdiction of the Illinois Tollway.

3.1.3 System Boundaries

The pavement system evaluated includes various upstream processes, such as fuel production and electricity generation, but excluding supporting production materials such as warm mix additives where data was not available. A commercial LCA database and software were used to model the products needed in the life cycle inventory, which allowed for a relatively complete consideration of upstream inputs and emissions. A diagram summarizing the system boundaries is included in Figure 3.2 on the following page. Major inventory items are discussed in detail in later sections of this chapter.

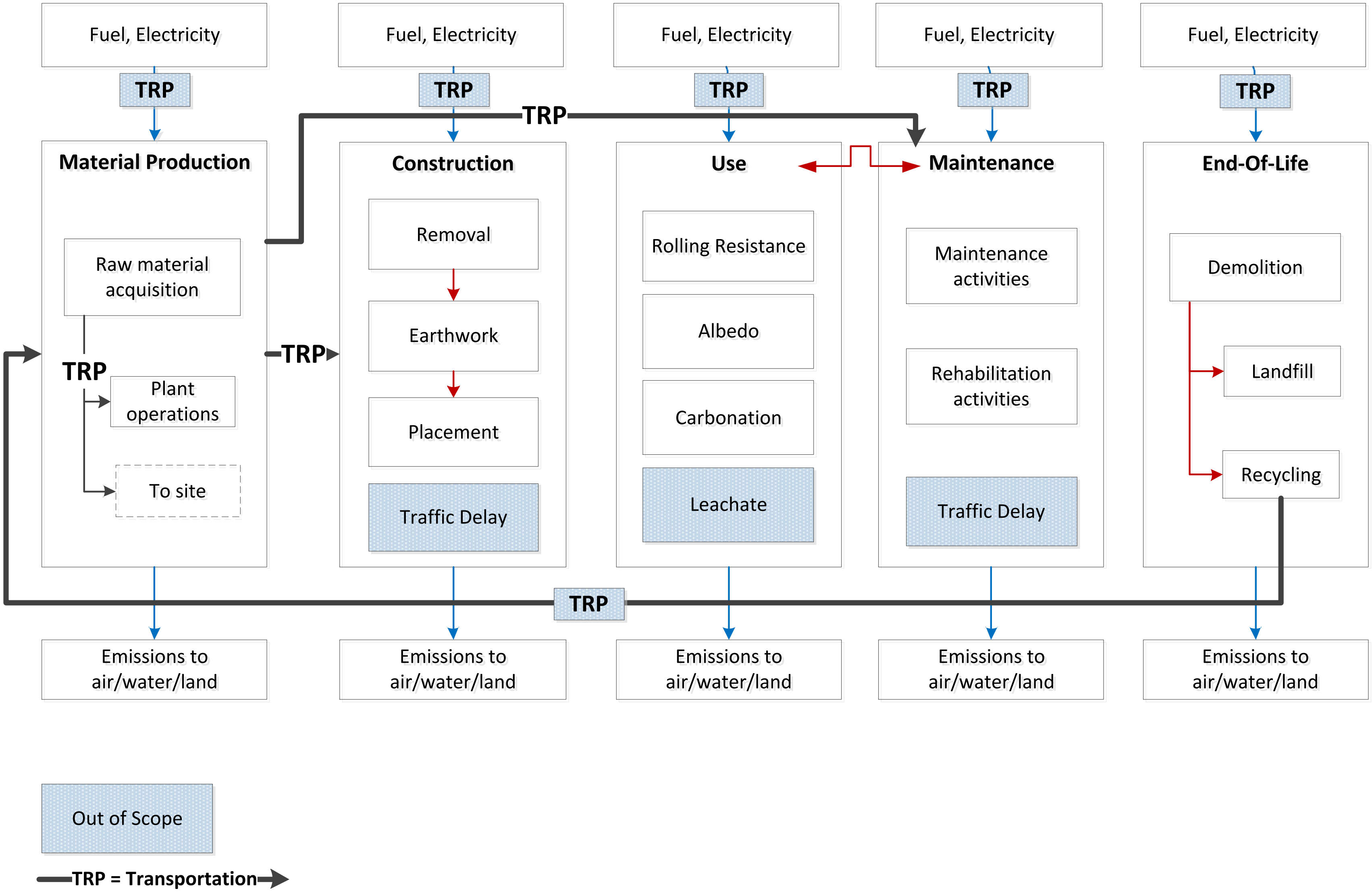


Figure 3.2 System boundaries for the study.

3.1.4 Data Collection and Methodology

In order to obtain a more comprehensive LCIA database (not only GWP), LCI data for the unit processes in this phase were modeled with a commercial LCA software, SimaPro 7.3.3. The commercial US-Ecoinvent 2.2 library database (US-EI 2.2) that is included with SimaPro 7.3.3 contains thousands of unit processes with detailed emissions to air, water, and land as well as lengthy records of natural inputs, energy use, transportation, and material needs. However, the US-EI 2.2 database was used directly only if no local data were available.

The US-EI 2.2 database was released in 2013 by EarthShift, and corresponds to the Ecoinvent 2.2 database (EI 2.2). Ecoinvent is published and updated regularly by the Centre for Life Cycle Inventories, which is supported by various Swiss institutes. Thus, the database is largely Eurocentric and contains limited U.S. data. The US-EI 2.2 library is a modified version of EI 2.2 that has substituted U.S. electricity processes, along with a few other processes, for corresponding processes in EI 2.2 and has also incorporated data from the USLCI database developed by the National Renewable Energy Laboratory (NREL). However, for the most part, the USLCI database has not been thoroughly reviewed, and an attempt has been made to avoid using USLCI processes in this study.

As mentioned, the Pavement LCA described in this study is intended to be a regional LCA that reflects, as closely as possible, processes from Illinois. Thus, the US-EI 2.2 unit processes were used to complement and supplement any external local data. Sources of external data included published reports, literature, open source databases, and locally distributed questionnaires. These locally distributed questionnaires were written and disseminated in conjunction with Applied Research Associates, Inc. to various contractors and plant operators working with the Illinois Tollway in the Illinois region. Details of the questionnaires received in 2012–2013 can be found in another work (Kang, 2013). The scope of external data included sources largely from a national content (e.g. U.S. slag cement production) or a regional context (e.g. Illinois electricity) depending on the data available.

The unit processes described in this chapter were modeled in SimaPro 7.3.3 based on available sources. The ultimate goal was to develop a regionalized inventory database for all of the unit processes; however, there is currently insufficient regional information to generate a complete database. The US-EI 2.2 database was used as a foundation for modeling in SimaPro 7.3.3. In an effort to further regionalize the inventory, processes from US-EI 2.2 were supplemented with data from regionalized questionnaires or literature sources whenever possible and appropriate. Four different levels regionalization were defined to describe the modeling approach in Table 3.1.

Table 3.1 Levels of Regionalization to Describe Modeling in SimaPro 7.3.3

<table>
<tr><th rowspan="2">Description of Regionalization</th><th colspan="4">Level of Regionalization</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>Choosing the unit process</td><td>Externally Specified</td><td rowspan="2">External Data</td><td rowspan="3">External Data</td><td rowspan="4">External Data</td></tr>
<tr><td>Quantities and types of supporting processes</td><td rowspan="3">US-EI 2.2</td></tr>
<tr><td>Amounts and types of fuel combustion and/or electricity</td><td rowspan="2">US-EI 2.2</td></tr>
<tr><td>Emission factors</td><td>US-EI 2.2</td></tr>
</table>

- Level 1 regionalization occurs if a unit process is chosen directly from US-EI 2.2 with little to no modifications. This occurs if no appropriate external sources are available. For example, for crushed aggregate production, Level 1 would be simply using the default process (i.e. *Limestone crushed, for mill*) in US-EI 2.2.

- Level 2 regionalization occurs if supporting processes from US-EI 2.2 are used to create a model in SimaPro 7.3.3. For example, a unit process for asphalt binder production can be made by compiling various higher level processes related to crude oil extraction, transportation, and refining. These supporting processes (i.e. *Crude oil, at production in North America*) are available in US-EI 2.2.

- Level 3 regionalization occurs if the fuel and electricity inputs needed to create the process locally are known. This level involves using existing US-EI 2.2 processes for fuel combustion in boilers, furnaces, etc. to model the unit process. For example, if the fuel consumption at an asphalt mixing plant is known, then the combustion processes (i.e. *Diesel, combusted in a generator*) can be used.

- Level 4 regionalization occurs if the emissions released during the unit process are known. This level of regionalization requires the most external information. For example, if the primary emissions from diesel combustion in a hauling truck are known, they can replace the primary emissions (i.e. *Carbon Dioxide*) in the default US-EI 2.2 process.

3.1.5 Impact Assessment

The impact assessment method chosen for this LCA study is the U.S. Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts Version 2 (EPA TRACI). This characterization method is the most widely used impact method in the U.S. A list of the impact categories can be found in Table 3.2.

Table 3.2 TRACI Impact Categories

Impact Category	Unit
Ozone depletion	kg CFC-11 eq
Global warming	kg CO_2 eq
Smog	kg O_3 eq
Acidification	kg SO_2 eq
Eutrophication	kg N eq
Carcinogenics	CTUh
Non-carcinogenics	CTUh
Respiratory effects	kg $PM_{2.5}$ eq
Ecotoxicity	CTUe
Fossil fuel depletion	MJ surplus

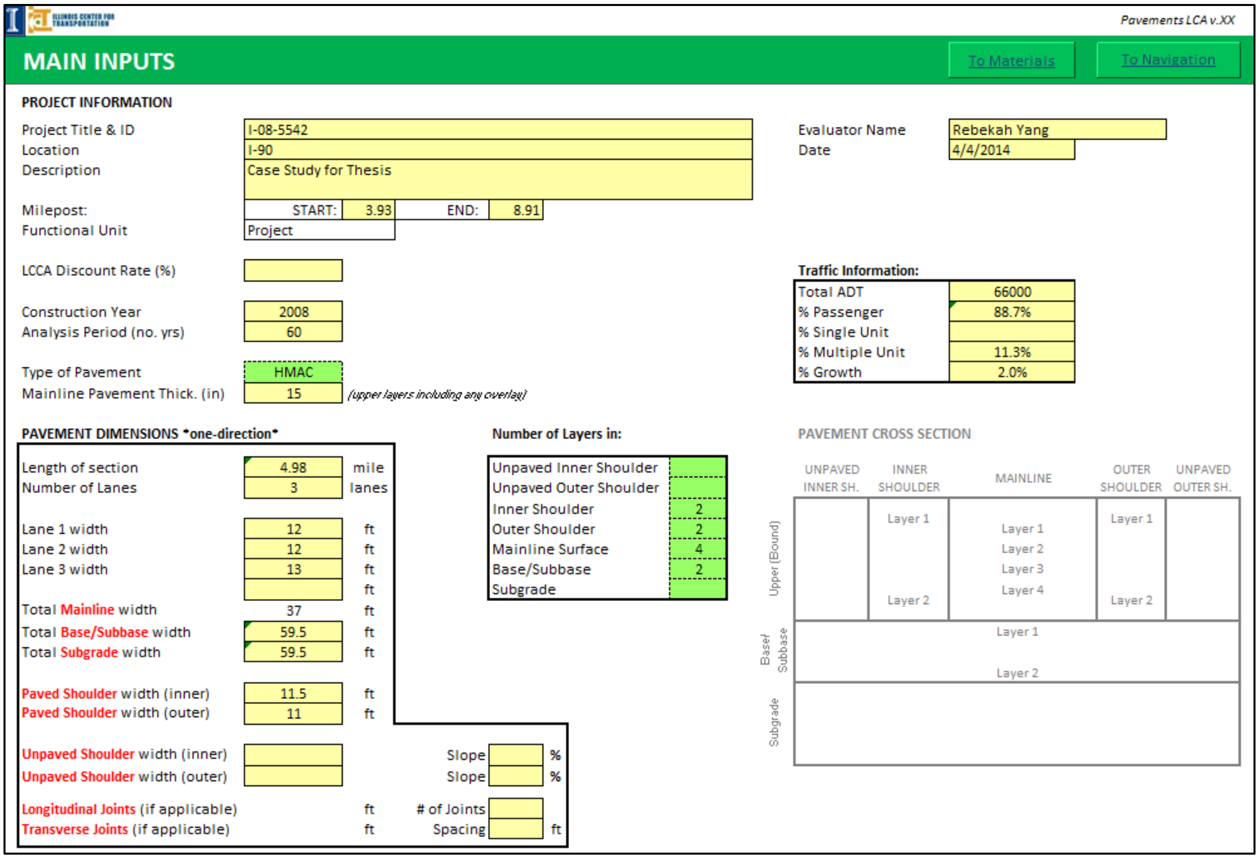
No normalization or weighting is considered in this study. In general, results from the global warming or GWP impact category calculated using TRACI are reported in addition to total energy consumption from inventory analysis.

3.2 Framework and Software Development

The Pavement LCA Tool (PLCA) was developed to be a standalone software in Excel®. Thus, the PLCA tool consists of one Excel® workbook with multiple worksheets, making it self-contained. It was implemented completely within spreadsheets without the use of macros. This section describes the overall framework and architecture of the tool.

3.2.1 System Architecture

The framework for the PLCA tool mimics the general LCA framework and follows a pavement design approach. The user first inputs basic geometries (e.g. length, widths, joint spacing) and characteristics (e.g. construction year, structure, traffic) of the pavement project in the *Main Inputs* worksheet. These geometries and characteristics are used throughout the rest of the PLCA to calculate volumes, tonnages, fuel consumption, etc. Figure 3.3 shows a screenshot of the *Main Inputs* worksheet.



PROJECT INFORMATION

Project Title & ID	I-08-5542			
Location	I-90			
Description	Case Study for Thesis			
Milepost:	START:	3.93	END:	8.91
Functional Unit	Project			
LCCA Discount Rate (%)				
Construction Year	2008			
Analysis Period (no. yrs)	60			
Type of Pavement	HMAC			
Mainline Pavement Thick. (in)	15	*(upper layers including any overlay)*		

Evaluator Name	Rebekah Yang
Date	4/4/2014

Traffic Information:

Total ADT	66000
% Passenger	88.7%
% Single Unit	
% Multiple Unit	11.3%
% Growth	2.0%

PAVEMENT DIMENSIONS *one-direction*

Length of section	4.98	mile			
Number of Lanes	3	lanes			
Lane 1 width	12	ft			
Lane 2 width	12	ft			
Lane 3 width	13	ft			
		ft			
Total **Mainline** width	37	ft			
Total **Base/Subbase** width	59.5	ft			
Total **Subgrade** width	59.5	ft			
Paved Shoulder width (inner)	11.5	ft			
Paved Shoulder width (outer)	11	ft			
Unpaved Shoulder width (inner)			Slope		%
Unpaved Shoulder width (outer)			Slope		%
Longitudinal Joints (if applicable)		ft	# of Joints		
Transverse Joints (if applicable)		ft	Spacing		ft

Number of Layers in:

Unpaved Inner Shoulder	
Unpaved Outer Shoulder	
Inner Shoulder	2
Outer Shoulder	2
Mainline Surface	4
Base/Subbase	2
Subgrade	

Figure 3.3 Screenshot of *Main Inputs* worksheet.

The user is then guided sequentially through each stage of the LCA using a series of worksheets and hyperlinks. The stages are modular and each contains a set of *Primary Inputs* and *Secondary Inputs* that the user can specify; however, the stages are not completely separate from each other. Some of the stages are interrelated, such as the use and maintenance phases, and some stages may share Secondary Input types. For example, the maintenance phase uses *Mix Designs* from the material phase as well as *Tasks* from the construction phase. Figure 3.4 on the following page contains a diagram of the overall architecture of the PLCA workbook.

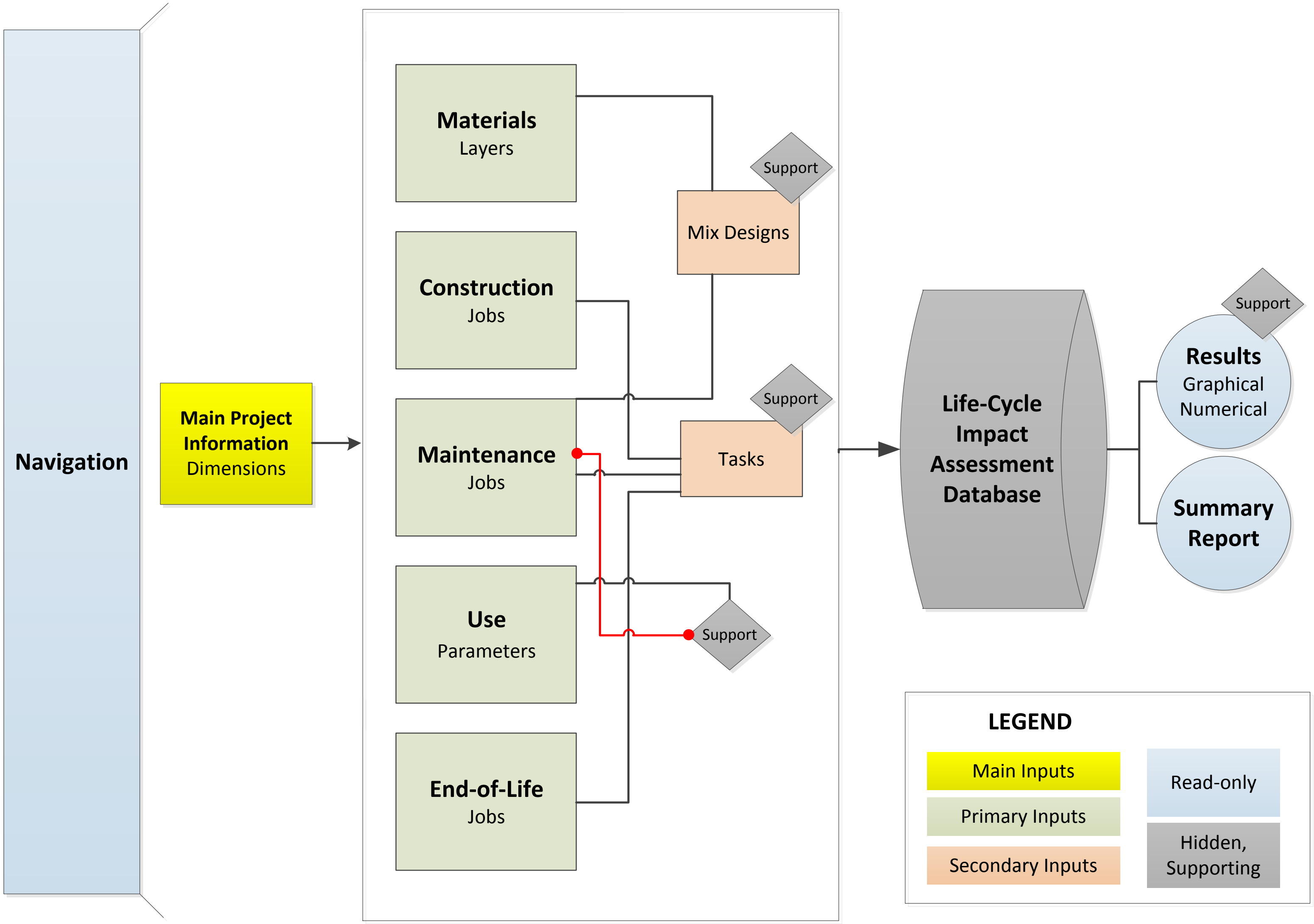


Figure 3.4 Overall architecture of the PLCA tool (where all shapes shown represent a worksheet).

3.2.2 Worksheet Categories

The PLCA tool contains nine different types of worksheets which are shown in Table 3.3. Some of the worksheets are interactive and visible to the user, while others are supporting or read-only worksheets that are hidden from the user.

Table 3.3 Worksheet Categories for the PLCA tool

	Category	Sub-sheets	No. of Sheets	Visible	Interactive
1	Navigation	---	1	V	I
2	Introduction	---	1	V	
3	Main Inputs	---	1	V	I
4	Primary Inputs	Layers; Jobs; Models	4	V	I
5	Secondary Inputs	Mix Designs; Tasks	2	V	I
6	Results	graphical; numerical	4	V	I
7	Summary Report	---	1	V	
8	Supporting	various	5		
9	LCIA Database	---	1		

3.2.3 *Main*, *Primary*, and *Secondary Inputs*

The *Main Inputs* are static and allow users to specify the major geometries and characteristics of the project, while the *Primary* and *Secondary Inputs* differ depending on the LCA stage. The relationships between the LCA stages and *Primary* and *Secondary Inputs* are shown in Figure 3.5.

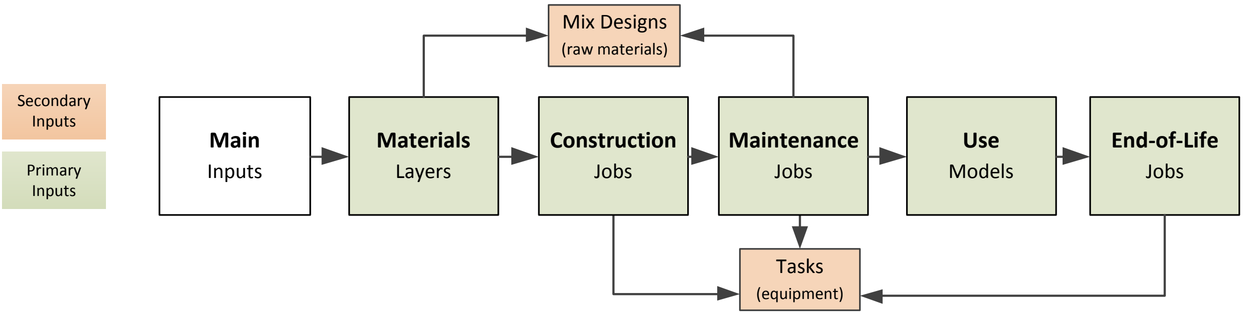
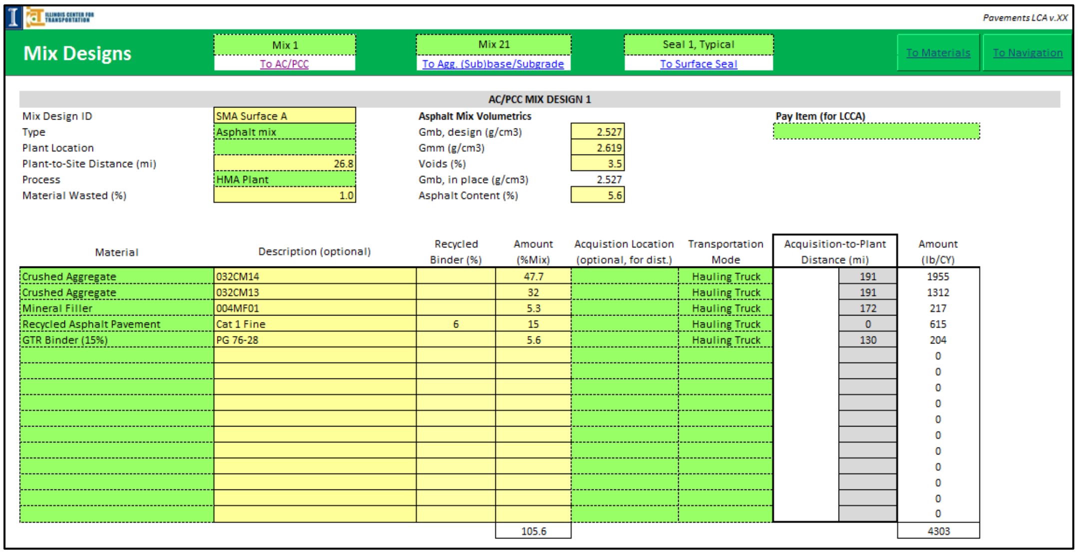


Figure 3.5 Relationship between *Primary* and *Secondary Inputs* for each stage.

There are two types of *Secondary Inputs* described below: *Mix Designs* and *Tasks*.

- The *Mix Designs* worksheet (Figure 3.6) is associated with the material production and maintenance phases. For each pavement mix in the project, the user can specific the mix type (e.g. asphaltic, Portland cement concrete, aggregate), the plant operation (e.g. hot-mix asphalt, warm-mix asphalt, ready mix concrete), percent waste, and the volumetrics for asphaltic mixtures. To define mixes, users specify for each material the type, amount or percentage, and transportation distance and mode to plant. The available material types are stored in the LCIA database and are described in Section 3.3.2.



AC/PCC MIX DESIGN 1

Mix Design ID: SMA Surface A
Type: Asphalt mix
Plant Location:
Plant-to-Site Distance (mi): 26.8
Process: HMA Plant
Material Wasted (%): 1.0

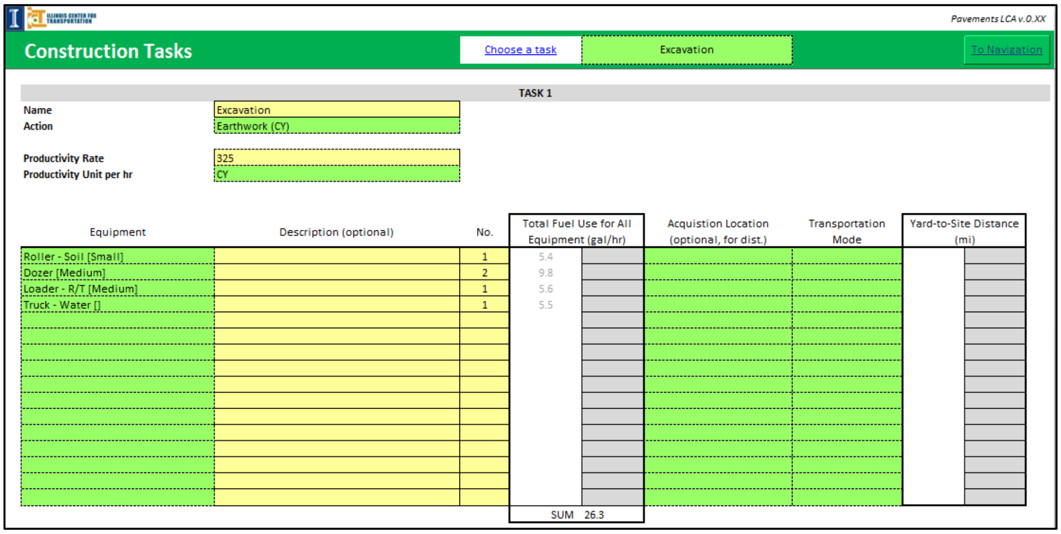
Asphalt Mix Volumetrics
Gmb, design (g/cm3): 2.527
Gmm (g/cm3): 2.619
Voids (%): 3.5
Gmb, in place (g/cm3): 2.527
Asphalt Content (%): 5.6

Pay Item (for LCCA)

Material	Description (optional)	Recycled Binder (%)	Amount (%Mix)	Acquistion Location (optional, for dist.)	Transportation Mode	Acquisition-to-Plant Distance (mi)	Amount (lb/CY)
Crushed Aggregate	032CM14		47.7		Hauling Truck	191	1955
Crushed Aggregate	032CM13		32		Hauling Truck	191	1312
Mineral Filler	004MF01		5.3		Hauling Truck	172	217
Recycled Asphalt Pavement	Cat 1 Fine	6	15		Hauling Truck	0	615
GTR Binder (15%)	PG 76-28		5.6		Hauling Truck	130	204
							0
							0
							0
							0
							0
							0
							0
							0
							0
							0
							0
			105.6				4303

Figure 3.6 Screenshot of the *Mix D*esign worksheet.

- The *Tasks* worksheet (Figure 3.7) corresponds to the construction, maintenance, and EOL phases. For each construction activity or task, the user can specific the task type (e.g. paving, removal, earthwork) as well as the productivity rate and unit per hour. To define the tasks, users specify for each equipment needed the type, number, and transportation distance and mode to site. The available equipment types in the LCIA database are summarized in Section 3.4.1.



TASK 1

Name: Excavation
Action: Earthwork (CY)

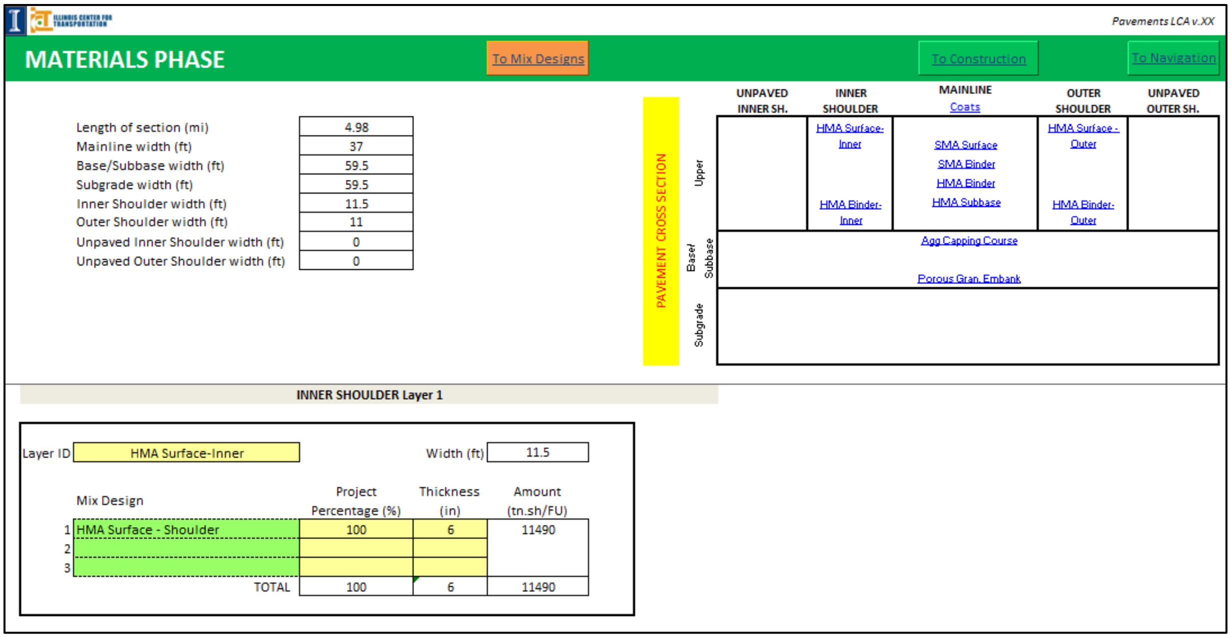
Productivity Rate: 325
Productivity Unit per hr: CY

Equipment	Description (optional)	No.	Total Fuel Use for All Equipment (gal/hr)	Acquistion Location (optional, for dist.)	Transportation Mode	Yard-to-Site Distance (mi)
Roller - Soil [Small]		1	5.4			
Dozer [Medium]		2	9.8			
Loader - R/T [Medium]		1	5.6			
Truck - Water []		1	5.5			
			SUM 26.3			

Figure 3.7 Screenshot of the *Tasks* worksheet.

Above the *Secondary Inputs*, there are three types of *Primary Inputs*: *Layers*, *Jobs*, and *Models*.

- The *Layers* worksheet (Figure 3.8) corresponds to the material production phase and calls upon the mixes defined in the *Mix Design* worksheet. Within the *Layers* worksheet, users can specify the mix designs and the corresponding percentages used in the project for each element in the pavement structure. These elements are specified in the *Main Inputs* worksheet and include the mainline, unpaved and paved shoulders, base or subbase, and subgrade.



MATERIALS PHASE

Length of section (mi)	4.98
Mainline width (ft)	37
Base/Subbase width (ft)	59.5
Subgrade width (ft)	59.5
Inner Shoulder width (ft)	11.5
Outer Shoulder width (ft)	11
Unpaved Inner Shoulder width (ft)	0
Unpaved Outer Shoulder width (ft)	0

	UNPAVED INNER SH.	INNER SHOULDER	MAINLINE Coats	OUTER SHOULDER	UNPAVED OUTER SH.
Upper		HMA Surface-Inner HMA Binder-Inner	SMA Surface SMA Binder HMA Binder HMA Subbase	HMA Surface - Outer HMA Binder-Outer	
Base/ Subbase			Agg Capping Course Porous Gran. Embank		
Subgrade					

INNER SHOULDER Layer 1

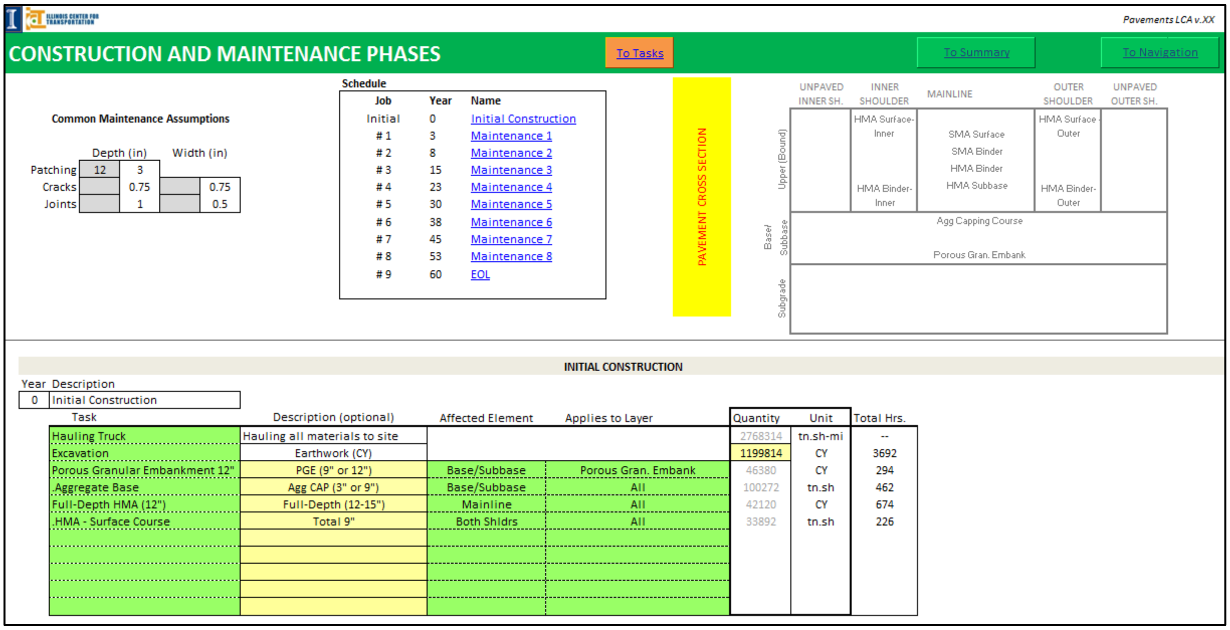
Layer ID: HMA Surface-Inner

Width (ft): 11.5

	Mix Design	Project Percentage (%)	Thickness (in)	Amount (tn.sh/FU)
1	HMA Surface - Shoulder	100	6	11490
2				
3				
	TOTAL	100	6	11490

Figure 3.8 Screenshot of the *Layers* worksheet.

- The *Jobs* worksheet (Figure 3.9) is used for the construction, maintenance, and EOL phases. The *Jobs* worksheet is populated with tasks defined in the *Tasks* worksheet. For construction and EOL, the user specifies the major tasks needed and the affected elements (e.g. a paving task for the surface layer of the mainline element). For maintenance and rehabilitation, the user can input a maintenance schedule that dictates the years that major maintenance will occur. For each of these years, a set of tasks, affected elements, and any additional materials (e.g. for patching or overlays) can be specified. The volumes, areas, tonnage or linear feet are automatically generated based on the affected elements selected.



CONSTRUCTION AND MAINTENANCE PHASES

Common Maintenance Assumptions

	Depth (in)		Width (in)	
Patching	12	3		
Cracks		0.75		0.75
Joints		1		0.5

Schedule

Job	Year	Name
Initial	0	Initial Construction
# 1	3	Maintenance 1
# 2	8	Maintenance 2
# 3	15	Maintenance 3
# 4	23	Maintenance 4
# 5	30	Maintenance 5
# 6	38	Maintenance 6
# 7	45	Maintenance 7
# 8	53	Maintenance 8
# 9	60	EOL

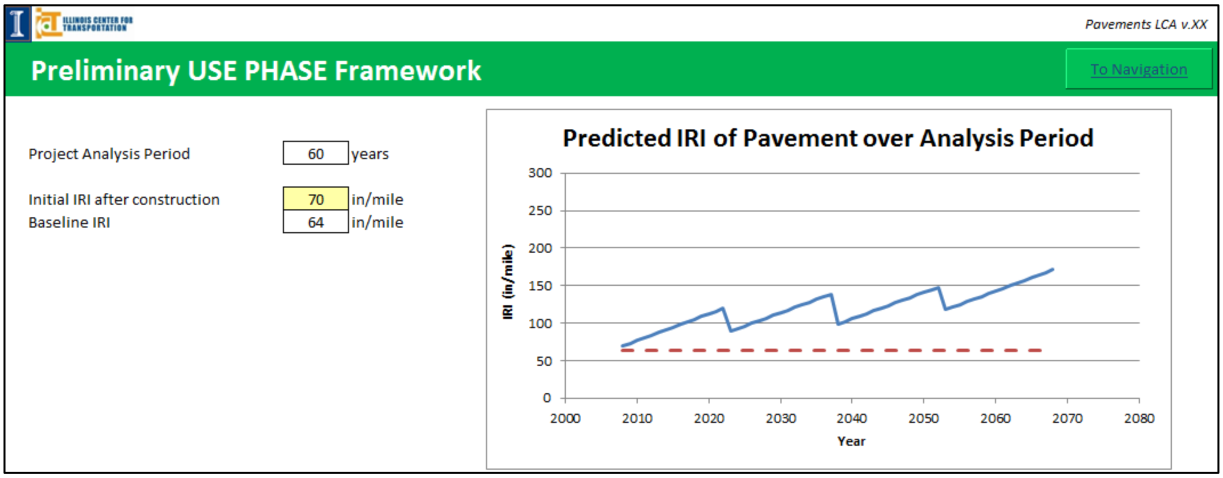
INITIAL CONSTRUCTION

Year	Description
0	Initial Construction

Task	Description (optional)	Affected Element	Applies to Layer	Quantity	Unit	Total Hrs.
Hauling Truck	Hauling all materials to site			2768314	tn.sh-mi	--
Excavation	Earthwork (CY)			1199814	CY	3692
Porous Granular Embankment 12"	PGE (9" or 12")	Base/Subbase	Porous Gran. Embank	46380	CY	294
.Aggregate Base	Agg CAP (3" or 9")	Base/Subbase	All	100272	tn.sh	462
Full-Depth HMA (12")	Full-Depth (12-15")	Mainline	All	42120	CY	674
.HMA - Surface Course	Total 9"	Both Shldrs	All	33892	tn.sh	226

Figure 3.9 Screenshot of the *Jobs* worksheet.

- The *Models* worksheet (Figure 3.10) does not draw from any user-defined *Secondary Inputs* worksheet. In the preliminary version of the PLCA, the user is asked to input the initial, post-construction international roughness index (IRI) and the corresponding IRI regression model is displayed in this worksheet. Only fuel consumption based on IRI is included in the preliminary version. The assumptions and model equations are stored in a hidden supporting worksheet.



Preliminary USE PHASE Framework

Project Analysis Period 60 years

Initial IRI after construction 70 in/mile
Baseline IRI 64 in/mile

Figure 3.10 Screenshot of the *Models* worksheet.

3.2.4 Calculations and Results

All of the calculations are performed in the numerical *Results* worksheet. The worksheet looks up the appropriate materials, plant operations, transportation, and equipment from the LCIA database and sums the impact factors based on the amounts needed from the *Primary* and *Secondary Inputs* worksheets. As suggested in ISO 14044, the impacts are first linked to the unit processes in the LCIA database during inventory collection. Then, using the tool, the impacts are consecutively summed at different levels (i.e. secondary, primary, phase, and finally project level) and ultimately related to the functional unit in the Results worksheet based on user inputs. Thus, the tool allows the user to examine the results at various levels, as shown in Figure 3.11.

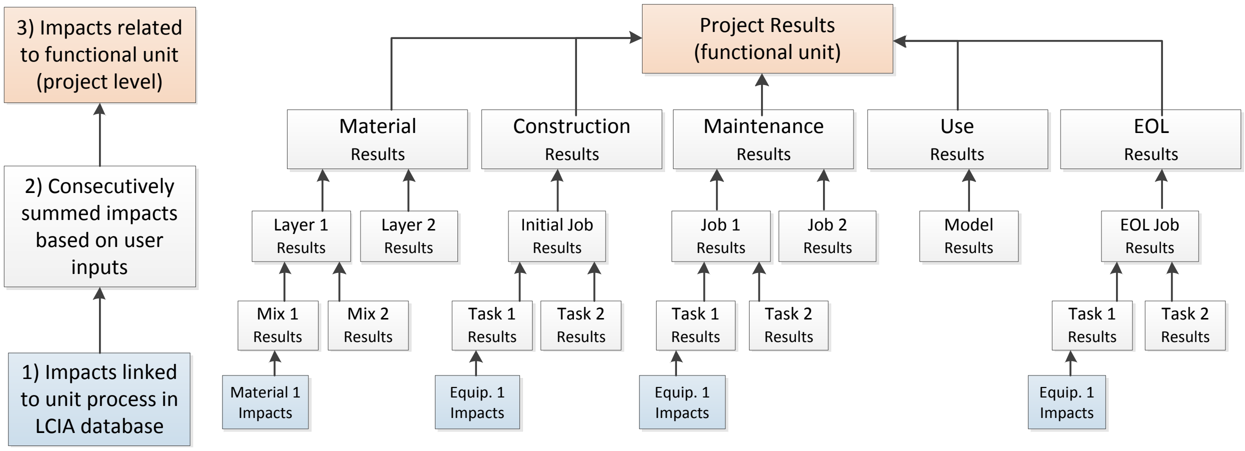


Figure 3.11 Results breakdown and visualization.

3.3 Material Production Phase

This section describes the approach used to model the material production phase of the pavement life cycle. The most significant component for this phase was the development of a LCIA database for all relevant material production and plant operation processes.

3.3.1 Methodology and Data Sources

The unit processes described in this section were modeled in SimaPro 7.3.3, using the US-EI 2.2 library and various external sources. The level of regionalization, as depicted in Table 3.1, depends on the data available and varies for each of the major processes that will be discussed. Whenever possible, local questionnaire data were used to model the processes, but when data were not reliable or available, other external sources were used. These sources may or may not reflect conditions found in the Northern

Illinois region, but care was taken to find sources as close to the region as possible (e.g. representing U.S. or Midwest processes rather than European processes).

3.3.2 LCI for Major Materials and Plant Operations

A brief description of the major assumptions and sources of each of the major materials and plant operations included in the LCIA database are given in this section. Additional details and validation of some of the material processes can be found elsewhere (Kang, 2013). A summary of the materials and plant operations with their energy and GWP values can be found in Table 3.4.

3.3.2.1 Aggregates production

Aggregates are a key component in every layer of the pavement structure for both flexible and rigid pavements. The production of aggregates is separated into that for crushed and natural aggregates. Crushed aggregate are those that undergo additional, mechanical breaking after acquisition or quarrying. The system boundaries for this process included quarrying and transportation (by conveyor belt) to the plant as well as crushing and washing at the plant (no secondary crushing or sieving). Natural aggregates, on the other hand, are not otherwise crushed or broken after acquisition, which is often done by dredging. The system boundaries for this process included dredging operations, screening, and internal transportation (for stockpiling).

In this study, the life cycle impacts of aggregate production were taken directly from the US-EI 2.2 database because the questionnaire responses received did not seem comparable to literature values. The process used to model crushed aggregate production was *Limestone, crushed, for mill/US*US-EI* and the process for natural aggregate was *Gravel, round, at mine/US*US-EI*. The crushed process was slightly modified to replace electricity generated from hydropower (a characteristic of the particular European facility the data was gathered from) to electricity generated from the Illinois grid.

3.3.2.2 Asphalt binder production

As a significant contributor to the life cycle impacts of flexible pavement, asphalt binder was selected to be the focus of an in-depth life cycle model that is detailed in Chapter 4. In addition to the straight binder LCI model that was developed in this study, modified binders, asphalt emulsion, and asphalt sealant were also considered in the LCIA database.

In addition to straight conventional binder, ground tire rubber (GTR) and polymer modified binder (PMB) are commonly used in the Illinois region. The system boundaries for GTR production included grinding, crushing, and mechanical pulverizing of scrap tire at a plant. It was also assumed that the ground tire is transported to a blending plant where it is blending in a wet process with binder and then stored in a heated tank. The inventory data for grinding the scrap tire came from one published study (Corti & Lombari, 2004), while the data for asphalt blending and storing were taken from another source (Wu et al., 2012).

The PMB considered in this study is styrene butadiene rubber (SBR) due to data availability, even though styrene butadiene styrene (SBS) is more commonly used by the Tollway. The system boundaries included the production of SBR, transportation of SBR to the blending site, SBR blending into the asphalt, and then storing the modified binder in tanks. The inventory data for PMB came for a variety of sources for the production of SBR (Fiksel et al., 2009), blending (Blomberg et al., 2011), and storage (questionnaire).

Asphalt emulsion and sealant are two important materials that are used in maintenance activities for surfacing and sealing cracks or joints, respectively. It was assumed that asphalt emulsion consists of approximately 60% binder, 1.5% emulsifier, and 38.5% water. The system boundaries for producing emulsion included transportation of emulsifier to blending site, heating of emulsifier soap (calculated), and high shear milling (Blomberg et al., 2011). No data was found for the production of emulsifier, so it was not included. The life cycle impacts for sealant were taken directly from US-EI 2.2, using the process *Bitumen adhesive compound, hot, at plant/US-US-EI*, substituting the study's binder model.

3.3.2.3 Portland cement production

Portland cement is a high contributing material in Portland cement concrete. For Type I cement, the processes for production included quarrying/crushing of limestone, raw meal preparation, pyroprocessing, and finish grinding. Items outside of the system boundaries included transportation of raw materials (e.g. iron, gypsum, etc.) as well as combustion emissions of waste fuels used in the clinker. The Portland Cement Association (PCA) has published life cycle inventories on cement production, and data from the latest report (Marceau et al., 2006) was used to model cement production in SimaPro 7.3.3.

3.3.2.4 Recycled asphalt materials

The recycled asphalt materials considered in the LCIA database include recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS). These materials are used in pavement because they both contain existing binder, which displaces a portion of the virgin binder that would otherwise be needed. This results in significant environmental and financial savings. RAP is often used as a partial aggregate and binder replacement in flexible pavements, while RAS is used as a partial binder replacement.

The system boundaries for RAP include crushing and screening of the RAP on site. The milling of RAP from the previous pavement and the transportation of RAP to the processing site were considered end-of-life activities from the previous pavements – a cut-off strategy was used. Similarly, for RAS, only the shredding and sieving of RAS was considered. In this study, questionnaire responses were used to obtain the fuel consumption for processing RAP and RAS. The RAS inventory data were much higher than reasonable, so the RAP data were used for both RAP and RAS production.

Finally, any feedstock energy contained in RAP and RAS was not considered. While it is true that recycled asphalt materials may retain their feedstock energy indefinitely, the percent retained is unknown and not accounted for in this thesis. There are two reasons for this negligence. First, the potential energy available from RAP and RAS may be affected by non-trivial processes needed to clean and extract the asphalt to use it as a fuel. Second, if feedstock is considered for both secondary (RAP and RAS) and primary (virgin binder) materials, an allocation must be used to distribute the energy to both types of materials to avoid double-counting. Thus, assumptions concerning whether the virgin binder will be recycled or disposed must be predetermined. Due to these uncertainties, the feedstock retained in recycled asphaltic materials is not considered, underestimating the total embodied energy in these materials where feedstock is considered.

3.3.2.5 Other materials

Fly ash is a cementious material that is often used as a partial replacement to Portland cement in Portland cement concrete or as fill in embankments. Fly ash is an industrial by-product from coal production. In this study, fly ash was considered as a waste product, so no allocation is given to its primary process. The system boundaries for this material included drying and stocking of fly ash and also transportation from coal production plant to treatment plant. The diesel and electricity needed for these processes were taken from a study (Chen et al., 2010).

Ground granulated blast furnace slag (GGBFS) is another industrial by-product that results from the production of pig iron. Similar to fly ash, it is commonly used as a cementious material in Portland cement concrete, replacing virgin Portland cement. GGBFS was also considered a waste product, so no allocation was given to its primary process. LCI data for this material were obtained from a 2004 report commissioned by the U.S. Slag Cement Association (Prusinski et al., 2004). The system boundaries included fuel use from granulating and grinding, in addition to the transportation associated with moving intermediary materials from furnace to granulators, granulators to grinding, and grinding to distribution.

Reinforcing steel is also an important component of Portland cement concrete. It is used in the form of dowels for Jointed Plain or Reinforced Concrete Pavements (JPCP, JRCP) and reinforcing bars for Continuously Reinforced Concrete Pavement (CRCP). It is assumed that the recovery rate of steel is 70% (SRI, 2012) and the recycled content is 35% (Ram et al., 2012). The default process from US-EI 2.2, *Reinforcing steel, at plant/US-US-EI*, was modified accordingly to incorporate recycling using the method detailed by the World Steel Association (2011).

3.3.2.6 Hot-mix-asphalt plant operations

Materials needed for asphalt pavement mixtures (binder, aggregate, additives) are transported to hot-mix-asphalt (HMA) plants for proportioning, mixing, heating, storing, and loading. Questionnaires responses from plants in the Illinois region were used to obtain LCI data in this study, where HMA plants use natural gas as a major fuel and are largely drum plants rather than batch plants. 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.

Plant operations for warm-mix-asphalt (WMA) were also considered. In addition to the processes considered for HMA, the transportation of WMA additives (3%) were assumed to be 200 miles by hauling truck. In addition, the effect of lower drum temperatures for mixing asphalt was accounted for by decreasing the natural gas used in the drum from a regression equation developed using data from an existing study (Young, 2008). The default HMA temperature and moisture were 300°F and 5%, while that for WMA were 265°F and 5%, respectively.

3.3.2.7 Ready mix concrete plant operations

Similarly, for Portland cement concrete, the materials (cementious materials, aggregate, admixtures) are delivered to a ready mix (off-site) or on-site plant for proportioning, mixing, and delivery. Local questionnaires from ready mix plants were used in this study. The system boundaries included diesel for in-plant loaders and generators as well as water for truck washouts. In future work, a process for on-site mixing plants should also be developed, as these types of plants are used for large construction projects.

3.3.2.8 Hauling truck

Local energy usage and emissions for hauling trucks in the northern Illinois region have been developed and documented in another thesis (Kang, 2013). These hauling trucks transport raw materials to plants as well as materials to construction sites. Kang used EPA's Motor Vehicle Emission Simulator (MOVES) to obtain LCI data for Combination Long-Haul Trucks in Cook County, Illinois in July 2010. The limited emissions and energy usage from MOVES replaced default values from the US-EI 2.2 process *Operation, lorry >28t, full, fleet average/US*US-EI*.

3.3.2.9 *Electricity generation*

The source of electricity generation can vary significantly among regions in the U.S. For the local material production and plant operations modeled in this study, all primary electricity used was modeled with an Illinois-specific process. This process was made in SimaPro 7.3.3 using EPA's Emissions & Generation Resource Integrated Database (eGRID) 2012 to obtain the distribution of source generation (e.g. coal, nuclear, hydro, etc.) for electricity in Illinois (U.S. EPA, 2012). The importance of using regional electricity models for refinery operations in binder production is discussed in Section 4.3.2. All other fuel production (e.g. natural gas, coal, diesel) are modeled using default US-EI 2.2 processes. In future work, the asphalt binder model described in Chapter 4 can be used to also model petroleum-based fuels such as diesel, gasoline, and residual oil.

3.3.3 Summary of Materials and Plant Operations

The TRACI method is used to calculate the GWP for each of the processes mentioned above. A summary of the GWP values and energy consumption values that make up the LCIA database for the material production phase are included in Table 3.4.

Table 3.4 Summary of Major Materials and Plant Operations Used in the LCA

Name	**Unit**	**Major Source**	**LOR**[7]	**GWP** kg CO_2E	**Energy** MJ
Straight Binder	tn.sh	EIA	3	274	4402
GTR (15%) Binder	tn.sh	Literature	3	347	5770
PMB (SBR)	tn.sh	Literature	3	386	7607
Emulsion	tn.sh	Assumptions	3	189	3160
Sealant	tn.sh	US-EI 2.2	2	380	6506
Cement	tn.sh	PCA	3	921	5745
GGBFS	tn.sh	Literature	3	155	2694
Fly Ash	tn.sh	Literature	3	58	1177
Reinforcing Steel	tn.sh	US-EI 2.2	2	1264	18851
Crushed Aggregate	tn.sh	US-EI 2.2	1	2.1	30
Natural Aggregate	tn.sh	US-EI 2.2	1	3.2	51
RAS*	tn.sh	substituted with RAP	3	1.3	17
RCA*	tn.sh	substituted with RAP	3	1.3	17
Steel Slag*	tn.sh	substituted with RAP	3	1.3	17
RAP	tn.sh	Questionnaire	3	1.3	17
HMA	tn.sh	Questionnaire	3	24	400
WMA	tn.sh	Literature	3	23	386
Ready Mix Concrete	CY	Questionnaire	3	6.5	89
Hauling	tn.sh-mile	MOVES	4	0.1	2
Illinois Electricity	kWh	eGRID 2012	4	0.6	14

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[7] LOR = Level of Regionalization

3.4 Construction and Maintenance Phases

This section briefly describes the LCA framework for the construction and maintenance phases. A more detailed report of these sections can be found in another thesis published from the Illinois Tollway project (Ferrebee, 2014).

3.4.1 Methodology, Data Sources, and Summary of Tasks

The system boundaries of these two phases include only the fuel production and combustion of the equipment needed in the construction tasks. Process-related emissions (e.g. VOC emissions from HMA paving) are not considered due to data availability and equipment manufacturing is excluded. Similar to the methodology used for processes in the material production phase, a combination of US-EI 2.2 and external sources are used. Only one US-EI 2.2 process (US-EI 2.2 process used is *Diesel, burned in building machine/GLO US-EI*) is available for generic construction equipment, so equipment-specific emissions from EPA's NONROAD2008 software were generated for Cook County in northern Illinois. The regional parameters used were similar to those used in EPA MOVES to model hauling trucks in Section 3.3.2.8. NONROAD2008 gives the following six emissions per gal of fuel burned for various equipment types and horsepower: CO_2, CO, SO_2, $PM_{2.5}$, and PM_{10}. These emissions were then merged into the US-EI 2.2 inventory and modeled in SimaPro 7.3.3.

A list of common tasks was generated to represent common construction activities performed during initial construction and maintenance. The productivity rates and equipment needed were taken from various published sources and existing software (Athena, 2013; Skolnik et al., 2013; World Bank, 2011) as well as references supplied by the Illinois Tollway. In the tool, the unit amounts for selected tasks are calculated based on the geometry of the affected pavement section (e.g. volume of CRCP to be paved, area of microsurfacing, etc.) and the productivity rate for the task is used to determine the fuel consumption for each equipment used in the task. A summary of major tasks with their productivity rates and fuel consumption are included in Table 3.5.

Table 3.5 Summary of Major Construction Tasks Used in the LCA

Task Name	**Productivity** per hour	**Unit**	**Fuel Usage** gal per hour
Grading, Earthwork			
Light Clearing	1089	SY	40
Medium Clearing	847	SY	52
Heavy Clearing	726	SY	52
Excavation	325	CY	26
Topsoil Strip & Stockpile	250	SY	3

Table 3.5 Summary of Major Construction Tasks Used in the LCA (cont'd)

Task Name	**Productivity** per hour	**Unit**	**Fuel Usage** gal per hour
Paving			
Aggregate Base	217	tn.sh	31
Asphalt Stabilized Subbase	42	CY	10
Porous Granular Embankment	158	CY	29
Full-Depth HMA	63	CY	10
Emulsion Application	11960	SY	3
Single-Lift JPCP	229	CY	12
Two-Lift JPCP	229	CY	24
Reinforcing Steel	1	tn.sh	5
Pavement Marking	10560	Linear FT	4
Maintenance			
Rout and Seal Cracks	394	Linear FT	7
Seal Joints	394	Linear FT	7
Crack Filling	394	Linear FT	7
Patching	13	SY	6
Milling	347	CY	31
Diamond Grind Surface	250	SY	4
Microsurface	1000	SY	5
Removal			
Asphalt Pavement Removal	50	CY	22
Concrete Pavement Removal	66	CY	18

3.5 Use Phase

The use phase is the most complex and underdeveloped phase in the pavement life cycle. The main components of the use phase are rolling resistance, albedo, concrete carbonation, lighting, and leachate (Santero et al., 2011a). Lighting is considered out of the scope of the LCA framework for this thesis, and only the remaining four components are discussed in this section.

3.5.1 Rolling Resistance

The interaction between pavement and vehicle affects the vehicle's performance, causing an increase in fuel consumption due to energy loss or rolling resistance (Santero et al., 2011a). Rolling resistance is influenced by the characteristics of the vehicle and tire system and the characteristics of the pavement system. The scope of this LCA considers only the contribution of the pavement system, and specifically, the roughness of the pavement as measured by IRI, without considering the structural effects of the pavement.

The IRI progression of the pavement must be predicted for the life cycle of the project. Both linear and exponential equations have been used to model IRI (Labi and Sinha, 2005; Wang et al., 2012). In this LCA, a simple linear model is used to predict the IRI progression of the pavement (Equation 3.1).

$$IRI(t) = IRI_0 + A \times t$$ **Equation 3.1**

The initial IRI immediately after construction is represented by IRI_0, and the simplified model determines IRI based solely on the age of the pavement t, measured in years. The rate of progression coefficient A can be determined from historical pavement condition data obtained from transportation agencies.

It is unclear as to whether maintenance activities (e.g. patching, crack sealing) affect pavement roughness. For example, an NCHRP study found that maintenance activities such as chip sealing, slurry sealing, and crack sealing do not reliably improve the roughness of the pavement (Hall et al., 2002). Therefore, in this thesis, it is assumed that only major rehabilitation activities (i.e. overlays) improve the IRI of the pavement while maintenances activities do not affect the IRI progression. Historical pavement condition data can be used to determine the initial drop in IRI that occurs immediately after a rehabilitation activity.

Another NCHRP study by Chatti and Zaabar (2012) estimates the vehicle operation costs as they are effected by various pavement conditions. One of the relationships calibrated in the study is the effect of change in IRI on vehicle fuel consumption. A linear relationship representing the percent increase in fuel consumption per 2 m/km increase in IRI was established by Chatti and Zaabar (2012) on a road profile with a mean profile depth of 1 mm (0.4 in) and 0% grade. The percent fuel increase (F_v) calculated per 1 in/mi increase in IRI is given in Table 3.6. The corresponding fuel efficiency, fuel type, and original US-EI unit processes are also shown. These fuel attributes are from the original US-EI 2.2 process, which have been modified with Illinois-specific emissions from MOVES. A modeling approach similar to that used for hauling trucks is also used for traffic vehicles, where upstream processes are from US-EI 2.2 and downstream emissions are modified with values from MOVES.

Table 3.6 Characteristics for Three Types Vehicles

Vehicle Type[8]	F_v (%)	MPG[1]	Fuel	Original US-EI 2.2 Process
Passenger	0.0379	30.8	Gasoline	*Operation, lorry >28t, full, fleet average/US*US-EI*
Single Unit	0.0126	15.9	Diesel	*Operation, passenger car/US-US-EI*
Multiple Unit	0.0229	5.2	Diesel	*Operation, lorry 7.5-16t, EURO3/US-US-EI*

[1] MPG values are from the original US-EI 2.2 process.

The change in IRI can be calculated using Equation 3.2 from the baseline IRI (64 in/mi) used by Chatti and Zaabar (2012). This equation allows for the comparison of pavements deteriorating at the same rate but with difference roughness. The functional unit of the vehicle operation processes from US-EI 2.2 is

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[8] Originally “medium car”, “light truck”, and “articulated truck” in the NCHRP report (Chatti & Zaabar, 2012).

expressed in terms of vehicle-miles traveled (VMT). Thus, the extra miles traveled (ΔVMT_v) for each vehicle is calculated by Equation 3.3, using the vehicle-specific increase in fuel consumption (F_v) per unit change in IRI from Table 3.6. The parameter R is the traffic growth rate, ADT is the average daily traffic, and P_v is the percent share of the vehicle type. The extra fuel consumption (ΔFC_v) is calculated using Equation 3.4 by dividing the extra VMT by the fuel efficiency (MPG_v) as found in Table 3.6.

$$\Delta IRI(t) = IRI(t) - IRI_{baseline}$$ **Equation 3.2**

$$\Delta VMT_v(t) = 365 \times ADT \times P_v \times (1+R)^t \times l \times \Delta IRI(t) \times F_v$$ **Equation 3.3**

$$\Delta FC_v(t) = \frac{\Delta VMT_v(t)}{MPG_v}$$ **Equation 3.4**

It should be noted that the method presented assumes that the change in IRI is the same for all ADT – i.e. the same across all lanes. It is more likely, however, that the *IRI(t)* is measured from the outer lane, which has the highest damage. Thus, the approach described above overestimates the extra fuel consumption. In future versions of the use phase, lane distribution factors should be considered to more accurately predict the extra fuel consumption over all lanes of the road segment.

3.5.2 Carbonation

Concrete carbonation refers to the process of free CO_2 rebinding to the cement in rigid pavements, resulting in a negative CO_2 impact. The free CO_2 will replace the CO_2 that is originally displaced during pyroprocessing of cement production. Carbonation can occur during the life cycle of a pavement and continue after removal and landfilling. However, the rate and efficiency of carbonation is difficult to model and can take a few years or a few thousand years to complete (Damtoft et al., 2008). In addition, carbonation occurs more quickly when the concrete is crushed. Thus, only the top few inches of the concrete will undergo carbonation during the pavement's service life, while the remaining carbonation may occur during the EOL phase depending on the situation (Santero et al., 2011a).

3.5.3 Albedo

Albedo is a measure that represents what proportion of shortwave radiation from the sun is reflected when it reaches a surface. If the radiation is completely absorbed, the surface has an albedo value of 0, and if the radiation is completely reflected, the value is 1. In urban areas, the albedo of pavement and roofing can have a significant effect on global warming and cooling (Akbari et al., 2009). Estimated albedo values for asphalt pavements are between 0.05–0.20 and for Portland cement concrete between 0.25–0.40 (Pomerantz et al., 1997).

There are two major effects of pavement albedo that are related to environmental concerns: urban heat island and radiative forcing. The urban heat island effect occurs in congested areas, where the radiation absorbed by the pavement increases the surrounding ambient temperature, resulting in increased energy use for cooling devices, such as air conditioning in buildings. However, the urban heat island effect is more applicable to city streets where warm weather is prevalent (Santero, 2009). The application of the LCA framework described in this thesis is for urban and rural highways, which arguably are not located close enough to buildings to significantly affect the surrounding ambient temperature. Thus, the urban heat island phenomenon will not be further considered in this thesis.

The second major effect of pavement albedo is a change in radiative forcing. Radiative forcing is a measure of the net change in radiation entering and leaving the Earth's atmosphere. It can be affected by a myriad of factors including atmospheric greenhouse gases, surface albedo, and the ozone. Negative radiative forcing results in a cooling effect while positive radiative forcing results in a warming effect. Akbari et al. (2009) calculated the effect of increasing pavement albedo on lowering radiative forcing and the resulting offset in atmospheric CO_2 emissions. The authors calculated a 2.55 kg CO_2 offset per square meter of urban area for a 0.01 increase in surface albedo. This offset is a one-time effect that occurs with a change in the pavement albedo (e.g. after an overlay or reconstruction).

3.5.4 Leachate

Leachate from the use of recycled material in the pavement structure may also be a component in the use phase. However, the pollutants from leaching by RAP have been found to be insignificant by past studies. The presence of volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons, and heavy metals were found to be below typical groundwater standards (Brantley and Townsend, 1999) and, in other study, weak and often below detection levels (Legret et al., 2005). Thus, any potential leachate pollutants from recycled materials is considered negligible in this study.

3.6 End-of-Life Phase

The EOL phase of a pavement is difficult to analyze due to uncertainty regarding the ultimate fate of the pavement: landfilled, recycled or kept in-situ (Santero et al., 2011a). In addition, pavements are often recycled into new pavement or other materials such as aggregate bases. When a material is recycled into another material, an open-loop allocation can be considered based on the ISO 14044:2006 definition regarding product systems. Three of the commonly applied allocation approaches to pavements include the cut-off method, substitution method, and 50/50 method. The cut-off method attributes the environmental burdens directly to the materials that they are associated with, so that the recycling benefit is given completely to the process using the recycled material. The substitution method is the opposite of the cut-off method, giving the recycling benefit to the process originally producing the material to be recycled. The 50/50 method gives half the benefit to each process.

In this thesis, a 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). The environmental impacts for producing and constructing as well as, if necessary, removing, transporting, and landfilling the pavement belongs to the existing pavement. Thus, the system boundaries of the new application begins either in the ground for in-place recycling or at the plant for off-site recycling. The energy required for in-place recycling and central plant recycling or crushing/screening belongs to the future pavement or application that will use the recycled material.

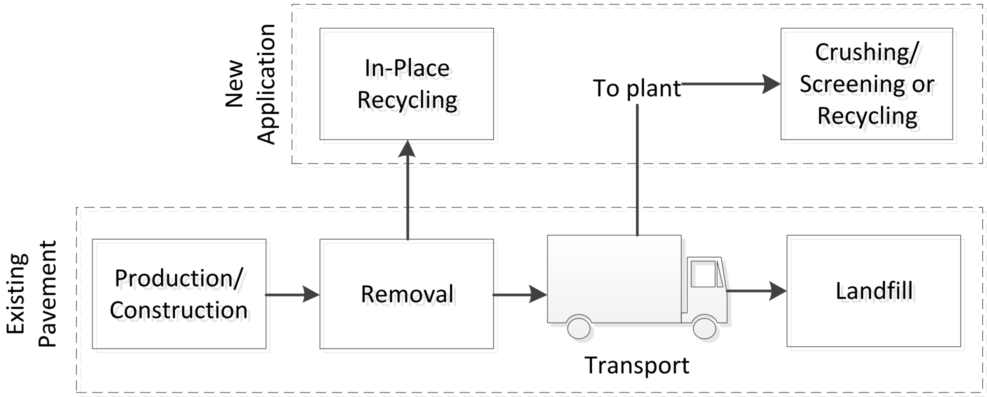

Figure 3.12 Cut-off approach for pavement.

The removal process for breaking or milling the pavement will be identical to the processes in the maintenance phase. A default US-EI 2.2 process, *Disposal, asphalt, 0% water, to sanitary landfill/US* US-EI U*, is used to model landfilling, while the crushing, screening and recycling processes are modeled with the RAP unit process. Ecoinvent considers short and long term emissions of landfilling without temporal discounting (Doka, 2013). Only short-term emissions are considered in the scope of this thesis, and thus all emissions in the 100 years after waste deposition are assumed to be in the same present time inventory. Thus, even though the analysis period of the LCA is 60 years, the emissions from landfilling will exceed 60 years.

4 Asphalt Binder Production Model

One important strategy in LCA is to focus on processes that will contribute significantly to the overall impact assessment. In the materials phase of the pavement life cycle, the production of asphalt binder is one of the most significant processes. While a mix design for flexible pavement may only contain 5–6% of this material by weight, asphalt binder can contribute 70% of the GWP impacts due to raw material production and 22% of the total material production phase including mixing plant processes (Kang et al., 2014). In this chapter, a framework for modeling the production of asphalt binder for various U.S. regions is described.

4.1 Objective and Scope for Binder Model

The objective of this task is to develop a procedure for calculating the life cycle impacts of asphalt binder production. Crude oil sources and refinery fuel consumption vary significantly among different regions in the U.S. Thus, with sufficient data, the procedure developed can be used to more accurate calculate the environmental impacts of binder production for various U.S. regions. In addition, crude oil sources are also heavily dependent on global geopolitical issues and can fluctuate with time. The framework developed in this thesis relies on readily available data that is updated weekly by the U.S. Energy Information Administration (EIA), so the inputs to the model can be updated to reflect future trends.

The following stages were considered in the asphalt binder LCA: crude oil extraction and flaring, crude oil transportation, refining, refined transportation, and blending and storage. The system boundaries did not include foreign operations beyond crude oil transportation to the U.S., as seen in Figure 4.1. The functional unit was one tn.sh of asphalt binder suitable for use in paving applications.

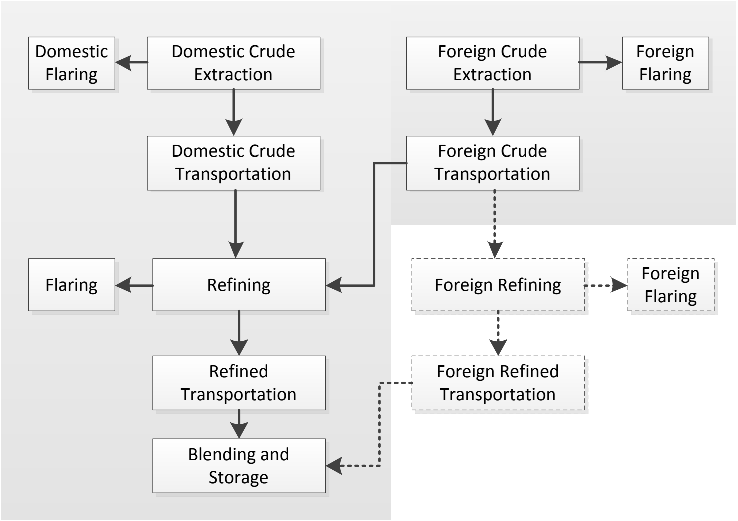

Figure 4.1 System boundaries for asphalt binder production.

In general, regionalized information from various publicly available sources was used whenever possible. To model unit processes, the US-EI 2.2 library was used for both higher level processes (e.g. crude oil extraction in Nigeria) and lower level processes (e.g. natural gas combusted in an industrial boiler). The following sections describe the calculations, assumptions, and sources of data for each stage in binder production. Life cycle impacts specific to five U.S. regions (East Coast, Midwest, Gulf Coast, Rocky Mountains, West Coast) were developed as well as impacts representing the average national binder production. Specific details are given for the Midwest region that contains the State of Illinois, but intermediary results for the other regions are also presented.

4.2 Crude Oil Processes

Crude oil processes include extraction, flaring, and transportation for both foreign and domestic crude sources. The EIA regularly publishes open source data about foreign and domestic crude oil production, imports, and movement, which were used heavily in this model (U.S. EIA, 2013). The data are compiled and published each year in EIA's Petroleum Supply Annual (PSA) reports, the latest of which is for the year 2012. The U.S. petroleum industry was organized into five Petroleum Administration for Defense Districts (PADDs) in the 1940's, as shown in Figure 4.2. The EIA reports historical data collected for each of these regions, and data between the years 2005-2012 were averaged for use in this study. The details given in this thesis are focused mainly on the PADD2 Midwest region, but life cycle impact results for each of the main PADDs as well as a U.S. average are also reported.

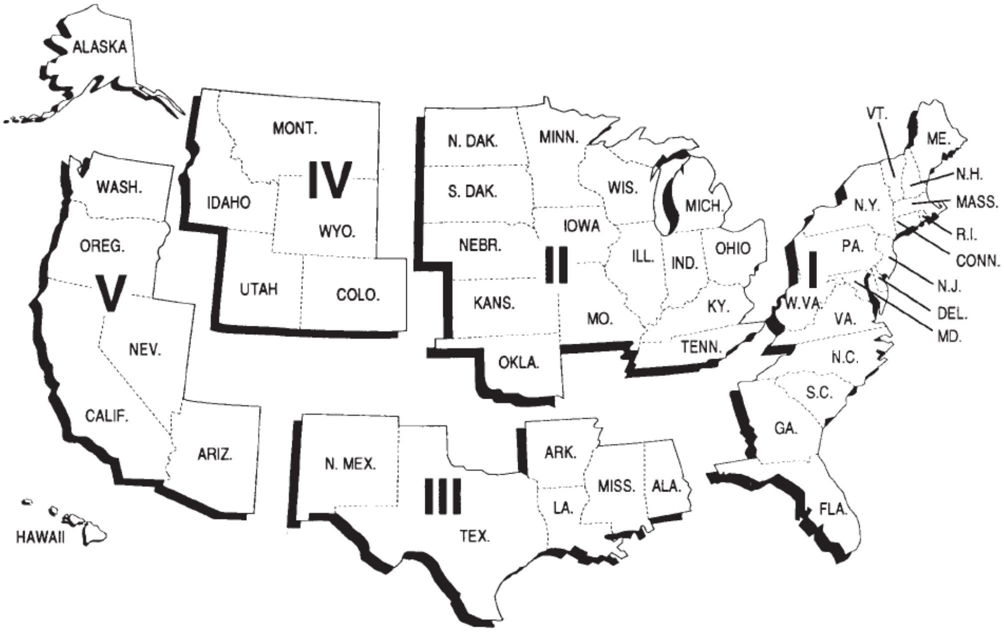

Figure 4.2 Geographical distribution of PADDs (U.S. EIA, 2013).

In order to maintain a mass balance, it was assumed that 1 tn.sh of the crude extraction, flaring, and transportation processes is necessary for 1 tn.sh of asphalt binder. However, this is not the case for the refining stage. As detailed later in Section 4.3, approximately 15.5 tn.sh of crude oil throughput are needed before 1 tn.sh of asphalt is refined in PADD2. Crude oil has a higher heating value (HHV) energy content than asphalt binder, which implies that there is a conversion energy loss. The energy content of crude oil was taken to be 42.7 MJ/kg (Swiss Centre, 2007) and the energy content of binder was assumed to be 40.2 MJ/kg (Garg et al., 2006). Thus, there is approximately a 6% inefficiency in the conversion of crude oil to asphalt binder, most likely occurring during the refining process. Feedstock energy of asphalt binder and refinery plant inefficiencies are addressed in Sections 4.3.5 and 4.4.3.

4.2.1 Crude Oil Distribution

The crude oil acquisition profiles of each PADD is unique due to its geographic location. Thus, it is important to consider different crude source distributions for each U.S. region. Crude oil source profiles were compiled for each PADD from EIA PSA reports and are summarized in Table 4.1. The profiles take into account the domestic and foreign crude sources for each PADD. Only the countries contributing more than 0.5% of the crude inputs to each PADD are considered in this analysis.

Table 4.1 Percentage of Foreign and Domestic Crude Sources for Each PADD (2005–2012)

Crude Source	PADD1 (East Coast)	PADD2 (Midwest)	PADD3 (Gulf Coast)	PADD4 (Rockies)	PADD5 (West Coast)	U.S. (National)
PADD1	-1.1	0.2	0.4	--	--	0.1
PADD2	1.2	12.5	1.6	11.4	--	4.2
PADD3	1.4	38.8	23.8		0.1	20.6
PADD4	--	4.9	0.1	39.5	--	2.5
PADD5	--	--	--	--	53.4	8.8
Foreign[9] (>0.5%)	NG 36.6	CA 37.5	MX 24.1	CA 49.2	SA 15.3	CA 19.6
	CA 24.3	SA 3.0	VE 17.8		EC 10.0	SA 12.9
	AO 13.6	DZ 1.3	SA 16.1		IQ 9.0	MX 12.4
	SA 13.1	NG 1.1	NG 10.0		CA 8.6	VE 10.2
	VE 10.9	AO 0.7	IQ 6.2		AO 3.6	NG 8.7
Domestic/ Foreign	1.5 / 98.5	56.5 / 43.5	25.8 / 74.2	50.8 / 49.2	53.5 / 46.5	36.2 / 63.8
Crude oil Processed	8.8	23.4	48.0	3.4	16.5	100

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[9] Country codes. NG: Nigeria, CA: Canada, AO: Angola, SA: Saudi Arabia, VE: Venezuela, DZ: Algeria, MX: Mexico, IQ: Iraq, EC: Ecuador

From the profiles, the Gulf Coast extracts the most crude oil but also imports 74.2% of its crude oil due to the high quantity of crude oil that the refineries in PADD3 process. The Midwest imports 38.8% of its crude oil from PADD3, and also 37.5% of its crude from nearby Canada. The Rockies, on the other hand, have the least diversity in crude sources, obtaining their imported crudes only from PADD3 and Canada. The differences in these profiles are important because they govern the inputs used to model crude oil extraction, flaring, and transportation.

4.2.2 Crude Oil Extraction

The processes of crude oil extraction vary from region to region, so it is important to match the most appropriate unit processes available to the crude source profiles for each PADD. For example, the International Association of Oil & Gas Producers (OGP) regularly publishes environmental performance indicators for the oil and gas extraction industry (OGP, 2012). The most recent database was released in 2012 and contains a summary of data collected from 41 companies representing 32% of global production sales. Energy consumption, emissions to air, and aqueous discharges are reported, aggregated for both oil and gas production by world region. The values for energy usage, summarized in Figure 4.3, show that clear differences exist among extraction processes worldwide.

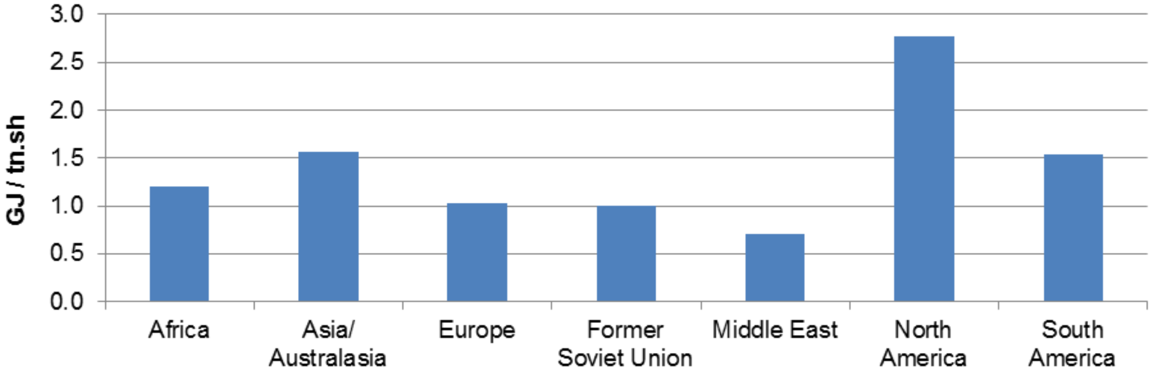

Figure 4.3 Energy consumption for hydrocarbon production in 2011 from OGP (2012).

For a more complete profile of life cycle inventory items for the extraction of crude oil, processes from US-EI 2.2 are used. The four relevant unit processes in Table 4.2 were identified in the US-EI 2.2 library and matched to each of the crude source locations found for the PADD regions. The system boundaries in the processes were modified to exclude flaring at the production site. Country-specific data was obtained for flaring, which is added separately, as discussed in Section 4.2.3. On the other hand, venting of gas at extraction site is kept as default from the US-EI 2.2 process as no other information is available.

Table 4.2 US-EI 2.2 Crude Extraction Processes and Their Corresponding Regions

US-EI 2.2 Process[10]	Matched Regions
*Crude oil, at production NREL/RNA**	U.S., all PADDs, Mexico , Ecuador, Venezuela, Canada
*Crude oil, at production onshore/RME**	Saudi Arabia, Iraq
*Crude oil, at production onshore/RAF**	Angola, Algeria
*Crude oil, at production/NG**	Nigeria

A few key assumptions were made. The unit processes from US-EI 2.2 were either explicitly for onshore production or represented a mixture of offshore and onshore production. OGP reports an average 56% reduction in energy consumption for global offshore production, which implies that the distinction is important (OGP, 2012). However, the amount of crude produced offshore in each region is not known and US-EI 2.2 processes are not available at such a detailed level for the relevant regions.

Next, no unit processes were available for South America, so the North American processes were used as a proxy. For example, Venezuela exports a significant amount of heavy crudes into the U.S. that requires more energy to extract and upgrade (Gerdes and Skone, 2009); however, the additional energy used to extract and upgrade heavy oils in Venezuela is not considered in this study due to insufficient information. Thus, the impacts for imported Venezuelan crudes are likely underestimated in this model.

Finally, oil recovery in Canada is modeled using a generic North American unit process. According to the Canadian Energy Board, approximately 53% of oil production in Canada from 2005-2011 is extracted through conventional oil well means, while the remainder is through unconventional means, such as oil sands (NEB, 2013). The North American process from US-EI 2.2 is most likely based on conventional extraction in the U.S. It has been estimated that the well-to-pump (extraction, transportation, and refining) GHG emissions for transportation fuels in the U.S. is 5–15% higher when oil sands are considered (CERA, 2010). A sensitivity analysis to observe the effect of considering oil sands on life cycle impacts for binder production in each PADD is discussed in Section 4.4.2.1.

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[10] An asterisk at the end of a US-EI 2.2 process name indicates that the original process was modified. In this case, flaring was removed in each process but venting was kept.

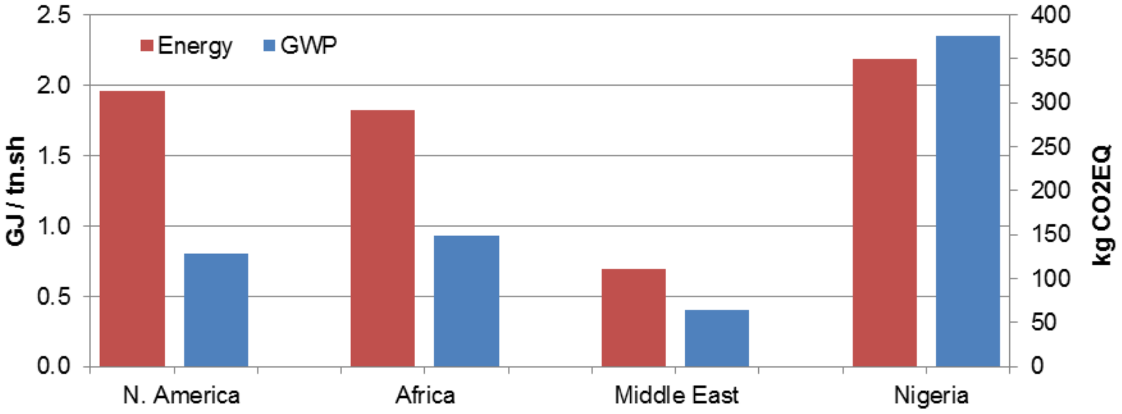

Figure 4.4 Comparison of various crude extraction processes from US-EI 2.2.

A comparison of the energy and GWP from the US-EI 2.2 unit processes for extraction are given in Figure 4.4. These regional values are consistent with the trends reported by the OGP in Figure 4.3. Extraction energy in North America is the highest, followed by Africa, and then the Middle East. The values for North America are underestimated in US-EI 2.2 because they are based on U.S. conventional extraction methods, and as discussed earlier, higher energy values are expected for unconventional methods. It is interesting to note that crude extraction in Nigeria is the highest, even without flaring. This is due to the high volume of natural gas venting in Nigeria (10 times that of Africa and the Middle East).

4.2.3 Flaring

Natural gas is a by-product of crude oil extraction that emerges to the surface along with oil during mining. When there is an insufficient gas infrastructure or market in the surrounding area to support the amount of natural gas that surfaces with crude oil, it can be released un-ignited (vented) or ignited (flared) (Unnash et al., 2009). The percentage of gas flared is unique to the extraction region, and the total global emissions resulting from flares constitute 1.5% of the world's CO_2 emissions.

Gas flaring for a number of countries has been regularly estimated by National Oceanic and Atmospheric Administration (NOAA) since 1994 (National Geophysical Data Center, n.d.). This project, funded by the World Bank's Global Gas Flaring Reduction Partnership, uses satellite images to estimate the volume of gas flared in 60 major oil producing countries. For the 10 countries relevant to this study, annual flaring volumes are normalized by annual crude production as reported by EIA between the years 2004–2011. The resulting average flaring intensity is shown in Figure 4.5 with one standard deviation. Nigeria is shown to have the highest flaring per unit crude while Saudi Arabia and the U.S. have the lowest.

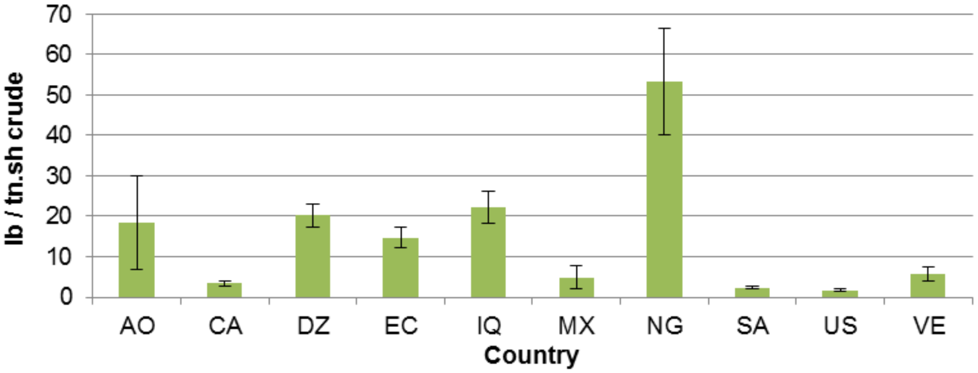

Figure 4.5 Flaring volumes for selected countries from NOAA (n.d.).

There are two relevant unit processes available in US-EI 2.2, one for sweet gas and one for sour gas flared at extraction site. Crude oil is considered "sweet" if the sulfur in the oil is more than 0.5% and "sour" if the sulfur is less. The impacts from the US-EI 2.2 processes show that sour gas has a slightly higher GWP (2.53 versus 2.46 kg CO_2E/m^3) when flared. The two processes are listed in Table 4.3 along with the regions that have been matched to each type of gas. In addition, the sour and sweet gas flared per tn.sh crude recovery for each PADD is shown in Table 4.4. In general, a higher sulfur content in the crudes will increase the upgrading and processing that must happen in the refinery (Skone and Gerdes, 2009). However, this effect was considered out of the scope in this study due to its complexity.

Table 4.3 US-EI 2.2 Flaring Processes and Matched Regions

US-EI 2.2 Process	Matched Regions
Natural gas, sour, burned in production flare/m3/GLO US-EI	Canada, Ecuador, Mexico, Iraq, Saudi Arabia, Venezuela, PADD3
Natural gas, sweet, burned in production flare/m3/GLO US-EI	Algeria, Angola, Nigeria, PADD1, PADD2, PADD4, PADD5

Table 4.4 Sour and Sweet Gas Flared (m^3/tn.sh crude) from EIA PSA (2005–2012)

Region	Sour gas	Sweet gas
PADD1	1.8	22.0
PADD2	2.0	1.2
PADD3	4.4	5.4
PADD4	1.7	0.8
PADD5	4.1	1.5
U.S.	3.4	5.1

4.2.4 Crude Oil Transportation

After considering the crude source profiles for each PADD, it is now feasible to accurately calculate the crude oil transportation from source to refining region. Crude transportation can be divided into foreign transportation and domestic transportation. A general description is given below, and a more complete record of the calculation of foreign and domestic transportation distances can be found in Appendix A.

Foreign crude transportation includes in-country transportation from the extraction site to terminal port as well as any overseas transportation from foreign port to entry port in the U.S. It was assumed that all in-country transportation is done via pipeline, and an average value of 100 miles was used (Skone and Gerdes, 2009). Overseas transportation is done via oil tanker, and the distances between probable foreign terminal ports and domestic entry ports were calculated using PortWorld's Distance Calculator (Portworld, 2014). It was further assumed that all overseas foreign crudes entered through Philadelphia or New Orleans. In the case of Mexico and Canada, foreign transportation was conducted on land via pipeline only. Pipeline distances for Mexico were estimated using Google Maps with Daft Logic's distance calculation tool (Daft Logic, 2014; Google, 2014). Pipeline distances for Canada were estimated similarly, following the Enbridge, Casper, and Trans Mountain crude pipelines.

For internal domestic transportation, EIA PSA gives the percent transportation by barge and pipeline of oil movement between PADDs. Thus, domestic transportation includes both pipeline and tanker movements between PADDs for domestic extracted oils as well as transportation between entry ports and final PADD destination for foreign extracted oils. Using the locations of existing oil pipelines and refining hubs as depicted by EIA's U.S. Energy Mapping System (U.S. EIA, 2014a), best-estimate pipeline distances were determined between each PADD as before. Offshore pipeline distances were estimated to be 70 miles for the Gulf Coast (PADD3) and 2 miles for the West Coast (PADD5). Distances for barge transportation were estimated using McDONOUGH's waterways calculator (2014).

The percent distribution of the crude sources was multiplied by the appropriate transportation distance to find the tn.sh-mile required for each transportation mode. A summary of the foreign and domestic transportation distances per tn.sh of crude input for each PADD is listed below in Table 4.5. Each transportation mode corresponds to a US-EI 2.2 unit processes that was used in the model (Table 4.6).

Table 4.5 Crude Oil Transportation Distances and Distribution (tn.sh-mi/tn.sh crude)

	Domestic Transportation			**Foreign Transportation**	
Mode:	Pipeline onshore	Pipeline offshore	Barge	Pipeline onshore	Oil Tanker
PADD1	960	0	19	99	4784
PADD2	851	12	0	44	423
PADD3	440	7	7	74	2967
PADD4	557	0	0	49	0
PADD5	1037	0	3	47	2620
U.S.	685	6	6	64	2374

Table 4.6 US-EI 2.2 Transportation Processes

US-EI 2.2 Process	**Matched Modes**
Transport, crude oil pipeline, onshore/US-US-EI	Domestic pipeline onshore
Transport, crude oil pipeline, offshore/OCE US-EI	Domestic pipeline offshore
Operation, barge tanker/US-US-EI	Domestic barge
Transport, crude oil pipeline, onshore/RER[11]	Foreign pipeline onshore
Operation, transoceanic tanker/OCE[3]	Foreign overseas oil tanker

4.3 Refining and Storage Processes

The next steps in the asphalt binder life cycle are refining, transportation to a blending terminal, and storage at the blending terminal. Data used to model the refining processes were also obtained from EIA PSA reports while storage energy needs were estimated using outside sources. As refining is a complex process with multiple outputs, many assumptions have been made using the limited data available. In addition, individual refineries themselves are not the same and varying according to inputs and outputs. The effect of crude oil properties, such as sulfur content, and American Petroleum Institute or API gravity (measuring the density of the oil with respect to water, similar in concept to specific gravity) were not considered to be within the scope of this study. For example, the need to upgrade heavy bitumen, such as those often exported from Canada and Venezuela, before refining was not considered.

4.3.1 Refining fuels

EIA PSA reports the amount of fuel consumed at refineries. This fuel includes both purchased fuel as well as refinery fuels, which were produced at some point during the refining process itself and now used as fuel for the process in a closed loop. The purchased fuel includes natural gas, coal, electricity, steam, and

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[11] This is in fact an original Ecoinvent 2.2 process rather than the modified US-EI 2.2 process.

natural gas used as feedstock for hydrogen production. A summary of the refinery fuel shares for each PADD is presented in Table 4.7. The fuel shares are fairly similar among the PADDs, but there are some differences that may affect the environmental impacts related to fuel combustion.

Table 4.7 Refining Fuel Percentage Shares for Each PADD

Refinery Fuel	PADD1	PADD2	PADD3	PADD4	PADD5	U.S.
Liquefied Petroleum Gases	0.29	0.49	0.09	0.14	0.83	0.33
Distillate	0.17	0.04	0.05	0.00	0.24	0.09
Residual Fuel Oil	1.23	0.13	0.01	0.32	0.76	0.28
Still Gas	46.11	47.21	43.71	44.51	43.73	44.63
Petroleum Coke	28.19	15.82	16.42	16.10	13.31	16.58
Other Products	0.11	0.50	0.50	0.52	1.56	0.67
Natural Gas	14.29	21.27	26.75	21.23	24.65	24.12
Coal	0.26	0.01	0.00	0.00	0.00	0.02
Purchased Electricity	5.18	5.91	4.69	5.38	2.95	4.67
Purchased Steam	2.09	1.70	4.10	0.95	2.76	3.10
Natural Gas Feedstock for H2	2.10	6.91	3.67	10.83	9.20	5.52

Combustion applications for each of these fuel types were assumed based on the GREET model. GREET's original combustion shares imply that some of the fuels are converted or used as inputs to be made into other petroleum products. However, the plant efficiencies calculated in Section 4.3.5 determine the total energy needed in the refining process excluding any inputs. Thus, it was assumed that none of the fuels were converted or used as inputs for other products, but rather, the fuels were 100% combusted for energy. The purchased steam was assumed to be produced from a natural gas boiler, and only the production of natural gas to be used for feedstock in H_2 production was considered. EIA PSA combines various petroleum products into "Other Products", which was assumed to be gasoline. The fuel combustion shares based on the GREET model and their corresponding US-EI 2.2 unit processes are shown in Table 4.8 on the following page.

Finally, it has been noted that while natural gas feedstock for hydrogen production at the refinery complex is included, hydrogen input from external sources is not included in the EIA data. The production of off-site hydrogen is considered to be out of the scope of this study, but other studies have included this input (Cai et al., 2013; Skone and Gerdes, 2009).

Table 4.8 Refining Fuel Combustion Shares and US-EI 2.2 Processes

Refinery Fuel	Share	US-EI 2.2 Process
Liquefied Petroleum Gases	1.00	*Liquefied petroleum gas, combusted in industrial boiler NREL/US*
Distillate	0.33	*Diesel, combusted in industrial boiler NREL/US*
	0.34	*Diesel, burned in diesel-electric generating set/GLO US-EI*
	0.33	*Diesel, combusted in industrial equipment NREL/US*
Residual Fuel Oil	1.00	*Residual fuel oil, combusted in industrial boiler NREL/US*
Still Gas	1.00	*Refinery gas, burned in furnace/MJ/US-US-EI*
Petroleum Coke	1.00	*Proxy_Petroleum coke, combusted in industrial boiler*[12]
Other Products	1.00	*Gasoline, combusted in equipment NREL/US*
Natural Gas	0.25	*Natural gas, burned in gas turbine/GLO US-EI*
	0.60	*Natural gas, burned in boiler modulating >100kW/US-US-EI*
	0.15	*Natural gas, burned in boiler modulating <100kW/US-US-EI*
Coal	1.00	*Bituminous coal, combusted in industrial boiler NREL/US*
Purchased Electricity	1.00	Various (see Section 4.3.2)
Purchased Steam	1.00	*Natural gas, burned in boiler modulating >100kW/US-US-EI*
Natural Gas Feedstock	1.00	*Natural gas, high pressure, at consumer/US-US-EI*

4.3.2 Electricity Used at the Refinery

Electricity contributes approximately 3-5% of the total fuel used at the refinery for each PADD, and is thus the fourth largest fuel quantity. The means by which electricity is produced varies widely across the U.S. For example, in Illinois, 46% of electricity was produced from coal generation and 49% from nuclear generation in 2012. In the surrounding states of Indiana and Iowa, the highest contributors were vastly different with coal (93%) and gas (3%) for Indiana and coal (72%) and wind (14%) for Iowa. Furthermore, on the West Coast, the electricity is generated largely by gas (56%), nuclear (16%), and hydro (14%) in California. Thus, the purchased electricity used by each PADD should be regionally appropriate (Delucchi, 1993a).

The US-EI 2.2 library includes electricity production categorized in the regions defined by the North American Electric Reliability Corporation (NERC). Thus, the task was to determine the regions that roughly corresponded with the PADDs. In order to better represent the electricity generated in the PADDs, the NERC regions were first matched to the Refining Districts[13] used by EIA. Using the location of major petroleum refineries in the U.S. Energy Mapping System, the NERC regions covering the refineries of largest capacities in each Refining District were selected to represent the electricity purchased in that district. The capacities of each Refining District were then used to proportion the

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[12] A US-EI 2.2 petroleum coke combustion was not found. Thus, a proxy process was created based on limited emissions for coke combustion used by the GREET model.

[13] The Refining Districts do not correspond directly to the PADDs.

appropriate share of electricity generation from each NERC region to the larger PADD region. The results of this process are summarized in Table 4.9.

Table 4.9 Electricity Generation Assumptions for each PADD

PADD	Refining District	Share	NERC Region	US-EI Process
1	Appalachian No. 1	0.07	RFC	*Electricity, at Grid, RFC, 2008 NREL/RNA*
	East Coast	0.93	RFC	*Electricity, at Grid, RFC, 2008 NREL/RNA*
2	Indiana-Illinois-Kentucky	0.65	RFC	*Electricity, at Grid, RFC, 2008 NREL/RNA*
	Minnesota-Wisconsin-North/South Dakota	0.12	MRO	*Electricity, at Grid, MRO, 2008 NREL/RNA*
	Oklahoma-Kansas-Missouri	0.23	SPP	*Electricity, at Grid, SPP, 2008 NREL/RNA*
3	Louisiana Gulf Coast	0.40	SERC	*Electricity, at Grid, SERC, 2008 NREL/RNA*
	New Mexico	0.01	WECC	*Electricity, at Grid, WECC, 2008 NREL/RNA*
	North Louisiana-Arkansas	0.03	SERC	*Electricity, at Grid, SERC, 2008 NREL/RNA*
	Texas Gulf Coast	0.49	TRE	*Electricity, at Grid, TRE, 2008 NREL/RNA*
	Texas Inland	0.07	TRE	*Electricity, at Grid, TRE, 2008 NREL/RNA*
4	Rocky Mountain	1.00	WECC	*Electricity, at Grid, WECC, 2008 NREL/RNA*
5	West Coast	1.00	WECC	*Electricity, at Grid, WECC, 2008 NREL/RNA*
	U.S.	1.00	U.S.	*Electricity, at Grid, US, 2008 NREL/RNA*

The energy consumptions needed to generate 1 kWh of electricity among some of the PADDs are notably different. In Figure 4.6, PADD4 and PADD5 have a higher percentage of electricity generated from renewable energy sources and a lower energy requirement overall.

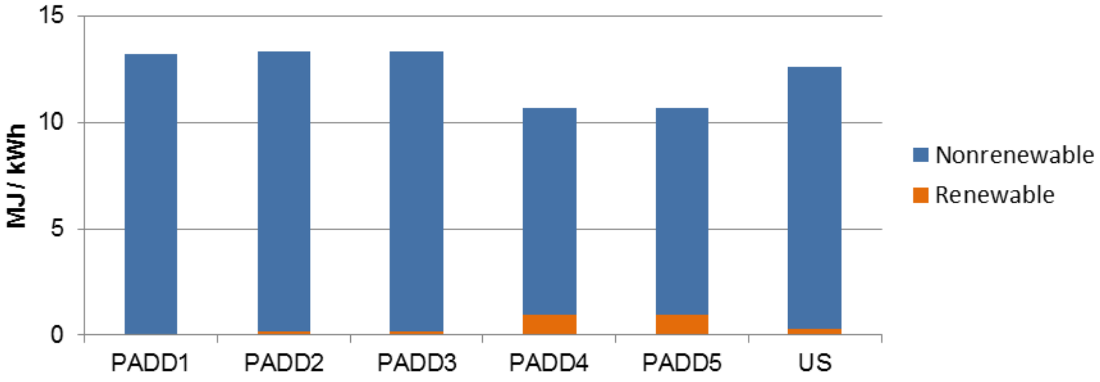

Figure 4.6 Energy consumed in the production of 1 kWh of electricity for each PADD.

4.3.3 Refinery Flares

Flaring during refinery operations often occurs during start up and shut down as well as when excess hydrocarbons cannot be safely recycled. The method to estimate refinery flares is adapted from another study (Skone and Gerdes, 2009). The South Coast Air Quality Management District in California has instituted requirements for refineries to report their flared volumes every quarter (SCAQMD, 2013). These values are published online for public access. In this study, average flared volumes are extrapolated from this source for use in each PADD, acknowledging the fact that the strict air quality regulations in California most likely underestimate the refinery flaring for other PADDs outside PADD5 West Coast.

A total of seven Southern California refineries are considered, and their average flaring volumes for 2010–2011 were normalized by their Atmospheric Crude Distillation Capacity (barrels per calendar day), as reported by EIA PSA. Limited emissions (CO, NO_x, SO_2, PM_{10}) are also given for each refinery, while combustion emissions (CO_2, CH_4, N_2O) were calculated by assuming that the flared gas has the composition of natural gas. The average emissions used for each PADD per tn.sh of the average refined product are below in Table 4.10.

Table 4.10 Average Refinery Flaring Emissions

Heat (Btu)	PM_{10} (lb)	NO_x (lb)	CO (lb)	SO_2 (lb)	N_2O (lb)	CO_2 (lb)	CH_4 (lb)
5133	1.58E-06	1.01E-05	2.28E-05	2.57E-05	4.26E-07	1.27E-02	7.29E-05

4.3.4 Asphalt Residue Rate and Crude Ratio

The term “residues” refers to the heavier crude components that remain in the bottom of the atmospheric distillation unit and are further processed in the vacuum distillation unit. These residues or “bottoms” ultimately become finished products such as asphalt, residual fuel oil or petroleum coke. In this thesis, the term asphalt residues refers specifically to the portion of residue that eventually becomes asphalt. EIA PSA uses the category “Asphalt and Road Oil”, which was assumed to be representative of asphalt suitable for general flexible paving applications.

The asphalt residue rate in a crude oil refinery can be estimated by the percentage share of asphalt produced out of the total petroleum products in the refinery. The crude-to-asphalt ratio can be defined as the units of crude oil needed to pass through the refinery before one unit of asphalt is made. The reciprocal of this ratio is a rate defined by the percentage share of asphalt out of the total crude oil input into the refinery. Thus, the crude-to-asphalt ratio is based on the total refinery input while the residue rate is based on the total refinery output. These two relationships can be slightly different due to processing losses or gains in the refinery. However, this effect is captured for all petroleum products using the plant efficiency concept described in Section 4.3.5. The asphalt residue rates and crude-to-asphalt ratios are included in Table 4.11 by both mass and volume.

Table 4.11 Asphalt Residue Rates and Crude-to-Asphalt Ratios for each PADD

Region	Residue Rate (%)		Crude-to-Asphalt Ratios	
	By volume	By mass	By volume	By mass
PADD1	6.3	8.2	17.5 : 1.0	14.2 : 1.0
PADD2	6.1	8.1	19.1 : 1.0	15.5 : 1.0
PADD3	1.3	1.8	79.7 : 1.0	63.2: 1.0
PADD4	6.7	8.9	14.9 : 1.0	11.7 : 1.0
PADD5	2.0	2.7	70.2 : 1.0	55.0 : 1.0
U.S.	3.1	4.1	36.4 : 1.0	29.1 : 1.0

The asphalt residues rates of oil refineries in the U.S. are between 1–9% of the total production. The differences in the residue rates show that the rate at which asphalt is produced varies from PADD to PADD, implying that the refining processes may be different or adjusted according to the particular crude input available or output desired. Allocation in the refinery is thoroughly discussed in Section 4.3.6, but in general, it is assumed in this study that the energy allocated to asphalt binder is directly and linearly related to the asphalt residue rate.

4.3.5 Plant Efficiencies

The inputs, outputs, and fuel consumed by the refinery are data that can be obtained from EIA PSA reports. Thus, it is possible to calculate the energy needed for the refining process using the concept of energy efficiency. This is the same method used in the GREET model to calculate the process energy needed for each stage in the transportation fuel life cycle (Wang, 1999a). The relevant equations are Equation 4.1 and Equation 4.2.

$$Efficiency\ (\eta) = \frac{Energy\ output}{Energy\ input} = \frac{Production}{Feed + \ Fuel} \qquad \textbf{Equation 4.1}$$

$$Process\ Energy = \frac{1}{efficiency\ (\eta)} - 1 \qquad \textbf{Equation 4.2}$$

The efficiency is thus represented in terms of energy output per energy input (e.g. MJ per MJ). The process energy is then similarly given in terms of fuel needed per energy output (e.g. MJ per MJ), absorbing the conversion loss between the energy difference between the reported inputted and outputted productions (approximately 1–3%). When calculating efficiency, the energy input includes both the feed (raw materials and intermediate materials that will be processed into petroleum production) as well as fuel consumed at the refinery. The fuel consumed at the refineries includes both purchased fuel as well as refinery fuels, as discussed in Section 4.3.1. The refinery production from EIA PSA was assumed to include the total net production of the refined products, including the refinery fuels. Likewise, the refinery input from EIA PSA was assumed to include the total net input needed for the production of all refined products, including refinery fuels. Using the energy content values for each petroleum product given by EIA (see Appendix A), the efficiencies for an average refinery in each PADD were calculated and are given in Table 4.12.

Table 4.12 Refinery Plant Efficiencies for each PADD

PADD1	PADD2	PADD3	PADD4	PADD5	U.S.
91.4%	90.3%	90.4%	90.9%	86.7%	90.0%

4.3.6 Allocation

ISO 14044 defines allocation as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (2006). ISO 14044 suggests that allocation be avoided whenever possible, but in the case of refining, only aggregated information is available from EIA for the entire refinery, so it is not possible to divide the refining process into sub-processes with limited data. Some other studies have broken down the refining process into sub-processes (e.g. Keesom et al., (2009), Skone and Gerdes (2009)), but this requires additional detailed information and is considered to be out of the scope for this study.

ISO 14044 then recommends that the inputs and outputs of the system be partitioned using a physical parameter (i.e. mass, volume, energy), and if this is not possible, to use other non-physical characteristics such as economic value. In the case of asphalt binder production, applying a physical allocation is not appropriate because there are no clear underlying physical relationship between asphalt binder and the other co-products in crude oil refining (Blomberg et al., 2011). According to ISO 14049 Technical Report, the physical ratio between asphalt and other co-products cannot be varied in the refinery without incurring significant, complex changes in the refining processes themselves. This implies that physical allocation is not applicable (ISO, 2000). Thus, an economic or market value allocation is used in this study. However, the effects of using other physically-based allocations are evaluated using a sensitivity analysis in Section 4.4.2.2.

The concept of using the market value of asphalt binder to allocate the appropriate energy consumption to the refining of asphalt binder is explained in Figure 4.7. This method has also been used previously to find allocation factors for asphalt binder using Illinois market prices (Aurangzeb et al., 2014).

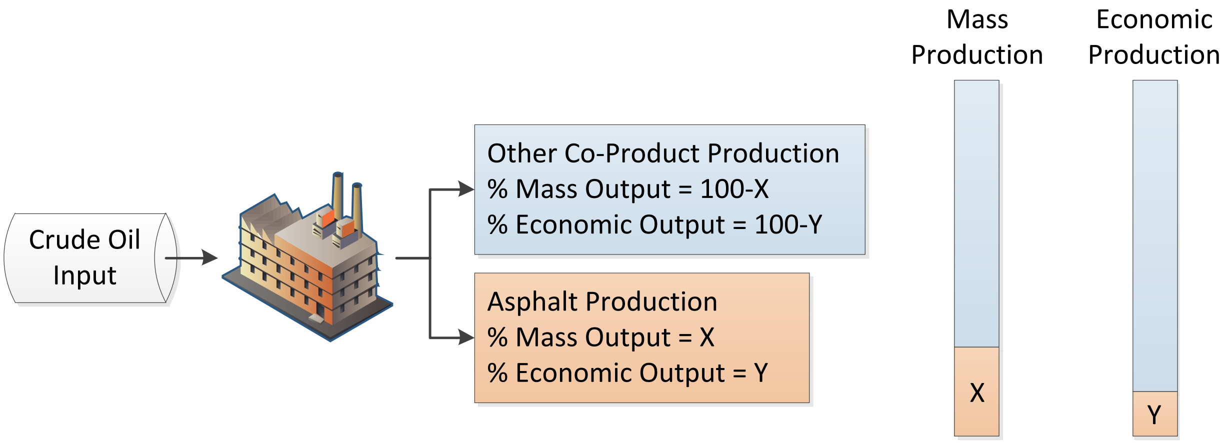

Figure 4.7 Concept of using market value as an allocation parameter.

Using mass as the base unit (because the impacts are known per mass unit of refined product), allocation attempts to relate the economic yield of asphalt to the mass residue yield of asphalt. The economic yield is considered the allocation coefficient, and can be substituted to represent parameters such as volume yield and energy yield, if other types of allocation are used. The allocation coefficient and mass residue yield are formally defined in Equation 4.3 and Equation 4.4. In Figure 4.7, "X" illustrates the mass residue yield and "Y" represents the allocation coefficient.

$$Allocation\ coefficient = \frac{Price_{asphalt} \times Yield_{asphalt}}{\sum_{p \in all\ products} Price_p \times Yield_p}$$ **Equation 4.3**

$$Mass\ residue\ yield = \frac{Yield_{asphalt}}{\sum_{p \in all\ products} Yield_p}$$ **Equation 4.4**

The allocation factor for asphalt is then determined in Equation 4.5 by taking the ratio between the allocation coefficient and the mass residue yield ("Y/X" from Figure 4.7). This allocation factor can be thought of as a relative energy proportion, representing the energy given to the production of asphalt as a fraction of the energy needed to produce the average mix of all of the petroleum products. Thus, it is assumed that the market value of a product is a direct, linear indicator of the energy needed to refine that product.

$$Allocation\ Factor = \frac{Allocation\ coefficient}{Mass\ residue\ yield} \times 100$$ **Equation 4.5**

For example, for PADD2, the allocation coefficient is 0.0344 while the mass residue yield is 0.0818. This means that only 3.44% of the total economic output of the refinery is asphalt, while 8.18% of the total mass output of the refinery is asphalt. The allocation factor calculated with respect to market value is 3.44/8.18= 0.42, which implies that the amount of energy allocated to asphalt should be 0.42 that of the average petroleum product. Thus, the amount of energy used in the refining of asphalt is less than half of that used in the refining of the average pool of refined products.

The allocation coefficients and mass residue yields were calculated for asphalt for each of the PADDs. The average market prices ($/mmBtu) and physical consumptions (thousand barrels) of each major petroleum product are recorded annually by EIA's State Energy Data System (SEDS) by state and sector (U.S. EIA, 2014b). Thus, in order to find the average market values for each PADD, a weighted average of the average market prices for all states in each PADD was determined. Using the energy contents, densities, and volume yields of each petroleum product, the allocation coefficients and mass residue yields were obtained for each product and reported in Table 4.13. The average market values and for each PADD are included in Appendix A.

Table 4.13 Allocation Factors for Various Petroleum Products Using Economic Allocation

Petroleum Product	PADD1	PADD2	PADD3	PADD4	PADD5	U.S.
Liquefied Petroleum Gases	1.51	1.26	0.69	0.90	1.06	0.76
Finished Motor Gasoline	1.23	1.23	1.13	1.13	1.23	1.13
Aviation Gasoline	0.00	1.38	1.23	1.20	1.24	1.21
Kerosene-Type Jet Fuel	0.95	0.96	0.95	0.96	0.97	0.94
Kerosene	1.19	1.22	1.00	1.27	0.00	1.21
Distillate Fuel Oil	1.13	1.15	1.21	1.21	1.27	1.20
Residual Fuel Oil	0.55	0.51	0.55	0.39	0.78	0.65
Petrochemical Feedstocks	0.00	0.00	0.61	0.00	0.00	0.77
Special Naphthas	0.94	1.04	1.00	0.00	0.91	0.99
Lubricants	2.81	2.82	3.20	0.00	3.23	3.14
Waxes	1.31	1.31	1.33	1.29	0.00	1.30
Petroleum Coke	0.06	0.08	0.12	0.07	0.13	0.14
Asphalt and Road Oil	0.42	0.42	0.42	0.37	0.45	0.50
Still Gas[14]	0.00	0.00	0.00	0.00	0.00	0.00
Miscellaneous Petroleum Products	1.00	1.02	1.02	0.68	1.03	1.00

The allocation factors for asphalt binder are in the range of 0.42–0.50. By comparison, the rates for gasoline and diesel are around 1.10–1.30, which seems reasonable due to their higher economic value. In

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[14] The economic value of Still Gas is assumed to be $0.00, as it is a by-product of refinery operations whose end use is assumed to be strictly within the refinery.

general, asphalt binder requires about half the energy to refine as compared to the average petroleum product if economic allocation is used.

4.3.7 Refined Transportation

The transportation of asphalt from the refinery complex to a blending terminal is assumed to be 50 miles by truck. Due to lack of information, a typical (non-heated) long haul combination truck used to model hauling trucks was also used to model this process. In reality, a tanker truck should be used to transport the binder.

4.3.8 Storage at Terminal

The energy required for storing the asphalt binder in heated tanks at the terminal was taken from a guidebook (May et al., 2003). The calculations assume that the tank temperature is maintained at 300 °F, 24 hrs a day for 30 days. The tank has a capacity of 30,000 gals of binder (240,000 lbs) with 3-in insulation. It was assumed that natural gas provides the fuel for the tank, and 1.128 mmBtu is needed to maintain the temperature for 24 hrs. The process listed in Table 4.14 was used to model the fuel combustion. The amount of hydrogen sulfide (H_2S) emitted during load-in and load-out was taken from a study (NCDAQ, 2003), but other emissions such as VOCs were not available for this study.

Table 4.14 US-EI 2.2 Storage Processes

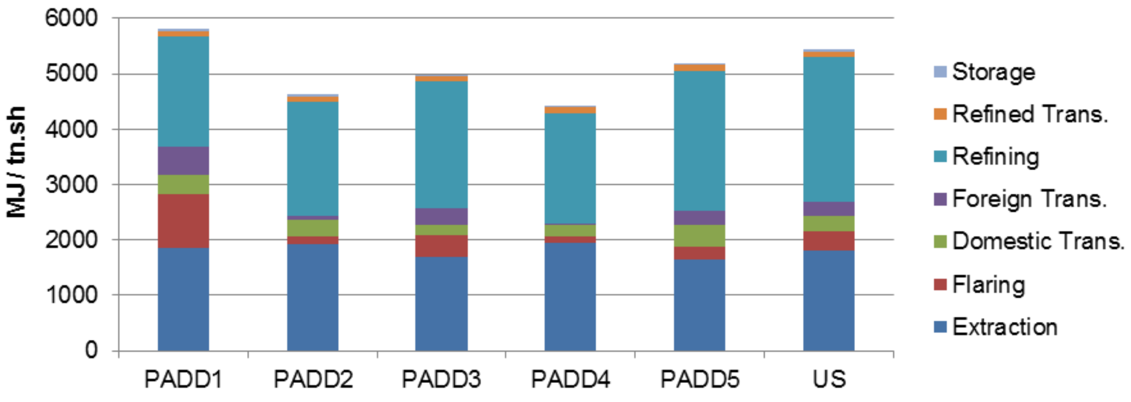
US-EI 2.2 Process	Matched Process
Natural gas, burned in boiler modulating >100kW/US-US-EI	Storage fuel

4.4 Results and Analysis

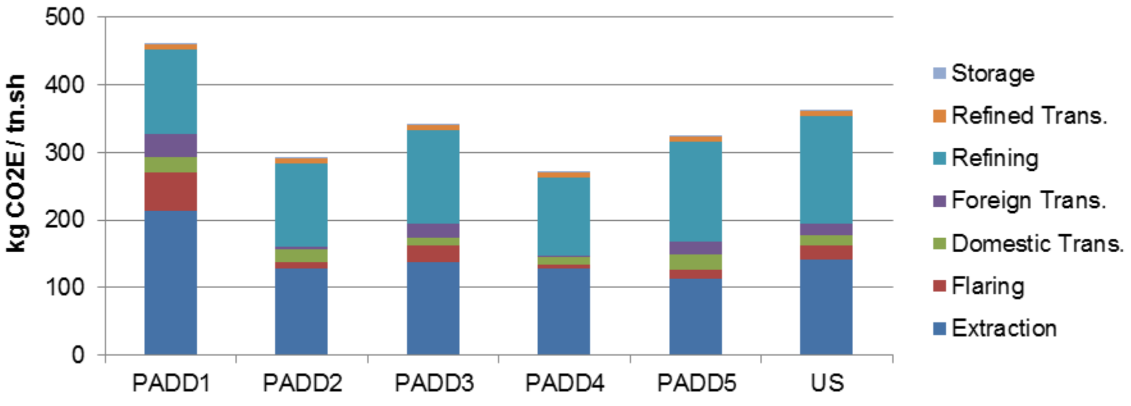
A complete framework for the life cycle of asphalt binder production has been described in this chapter. The boundaries of the system include crude oil extraction, flaring, and transportation as well as refining, refined transportation, and storage. The results of this model for each PADD are presented in this section. In addition, two sensitivity analyses are discussed regarding the consideration of Canadian oil sands and refining allocation.

4.4.1 Results for Each PADD Regions

The impacts studied in this model included global warming potential as well as energy consumption. Figure 4.8 shows the asphalt production impacts for all PADDs as well as the U.S. national average. The full list of impact categories from TRACI for each PADD can be found in Appendix A.



(a)



(b)

Figure 4.8 Life cycle results for all PADDs for (a) energy and (b) GWP.

It is clear from the figures that asphalt binder production in each PADD does have different magnitudes of life cycle impacts. When comparing the region with the highest environmental burdens (PADD1) and that with the lowest burdens (PADD4), a difference of up to 24% in energy consumption and 41% in GWP can be seen. PADD1 East Coast has the highest GWP and energy consumption, mostly due to flaring and foreign crude transportation. PADD1 imports 98.5% of its crude, with 36.8% coming from Nigeria, a country known to have high flaring with extraction. PADD4 Rockies imports only 49.2% of its crude, all of it coming just across the border from Canada. The U.S. average is relatively high due to the geographical distribution of crude processing among the regions: 9% PADD1, 23% PADD2, 48% PADD3, 3% PADD4, and 17% PADD5. The model for PADD2 Midwest is used in the overall pavement LCA developed for the Illinois region as presented in the latter chapters of this thesis.

4.4.2 Sensitivity Analyses

4.4.2.1 Canadian Oil Sands

Oil imports from Canada make up a large part of the crude input into U.S. refineries, with a national average of 19.6%, ranging from almost 50% in PADD4 and 9% in PADD5. Thus, it is important to consider the effect that oil sands can have on the binder life cycle. The Canadian National Energy Board publishes annual shares of the types of crude oil that are produced in each territory (NEB, 2013). The types of crudes are categorized into Conventional Light and Condensate, Conventional Heavy Crude Oil, Synthetic Crude Oil, and Non-upgraded Bitumen. Between 2005–2012, 50% of Canadian oil production came from conventional methods while 50% from unconventional methods. In addition, of the 50% oil sands, 54% was upgraded to synthetic crude oil and 46% was non-upgraded.

There are various types of unconventional methods of crude extraction. In Canada, approximately 20% of the unconventional crude is extracted via surface mining while 80% is extracted via in-situ methods such as thermal steam injection (CERA, 2010). In general, in-situ production has a higher energy consumption than surface mining due to the production of steam. According to assumptions from the GREET model, in-situ extraction requires 8.1 times the energy as compared to the average conventional extraction methods, while surface mining and upgrading require 2.4 times more energy. In this study, the energy values from GREET is not used because the percentage of crude produced by in-situ methods and surface mining are not known.

However, a recent summary report by IHS Cambridge Energy Research Associates (IHS CERA) found that the relative GHG emissions of oil sands to conventional oils as reported by various sources are inconsistent due to system boundaries (2010). Some claim that the production of oil sands require five times more energy, while others three times more energy than conventional crude. The former may be true if upgrading is included, while the latter if it is excluded. Instead, IHS CERA recommends to compare conventional and unconventional oils through the refining stage, as synthetic crude oil is partially processed and thus emits 45% less GHGs during refining.

Most related studies on oil sands include only additional GHGs and not energy consumption incurred during extraction. Thus, in this sensitivity analysis, it is simplistically assumed that the GHGs and energy consumption are linearly related (i.e. a 45% reduction of GHGs in refining corresponds to a 45% reduction of energy needed in refining). NREL’s baseline report gives GHGs collected from two major Canadian oil sands producers as 81.4 kg CO_2E and 133.9 kg CO_2E per barrel crude for blended bitumen and synthetic crude oil, respectively (Skone and Gerdes, 2009). Compared to the 19 kg CO_2E per barrel crude[15] from the US-EI 2.2 North American crude extraction method, the relative energy ratios for extraction and refining are given in Table 4.15.

Table 4.15 Energy Ratios for Oil Sands and Conventional Oil Extraction and Refining

Process	U.S. Conventional	Canadian Oil Sands	
		Blended Bitumen	Synthetic Crude Oil
Extraction only	1.0	4.2	6.7
Refining only	1.0	1.0	0.65

Using the modified energy ratios above and the assumption that 54% of import Canadian oil sands are synthetic crudes while 46% are blended bitumen, the life cycle GHGs and energy consumed for asphalt binder production were re-calculated for each PADD. The resulting increases in GHGs are shown in Table 4.16 when considering well-to-storage and only the extraction stage.

Table 4.16 Effect of Considering Oil Sands on GHGs on Asphalt Production for Each PADD

Scenario	Percent Oil Sands of Total Crude (%)	Well-to-Storage Increase in GHGs	Extraction Stage Increase in GHGs
PADD1	12.2	1.2	1.3
PADD2	18.8	1.4	1.9
PADD3	0.0	1.0	1.0
PADD4	24.6	1.5	2.1
PADD5	4.3	1.1	1.2
U.S.	9.8	1.2	1.4
All Synthetic Crude Oil[16]	100.0	2.9	6.3
All Blended Bitumen[16]	100.0	2.1	3.8

The All SCO and All Blended Bitumen results are higher than the numbers reported by IHS CERA. The literature asserted that transportation fuel from oil sands surface mining has 1.4 times the well-to-pump GHG emissions as the average fuel consumed in the U.S., and transportation fuel from oil sands in-situ methods has 1.7 times the emissions (CERA, 2010). This study instead shows factors in the range of 2.1–2.9 for transportation fuels produced from oil sands. However, the results of these two studies are not directly comparable because the IHS CERA focuses on transportation fuels (i.e. diesel, gasoline), which can have much higher refining allocations than asphalt. If the economic allocation values for Finished Motor Gasoline (Table 4.13) are used instead of the asphalt allocations for refining, than the factors are between 1.7–2.1, which are more similar to those found by IHS CERA. Regardless, the consideration of

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[15] The GHGs from domestic (U.S.) crude oil extraction given in NREL is higher at 25.4 kg CO_2E per barrel.
[16] In these cases, 100% crude input is from Canada, and the results are compared to the U.S. average without considering any oil sands.

oil sands can have a significant effect on the environmental impacts associated with the life cycle of asphalt binder and should be included in future work.

4.4.2.2 Refining Allocation

An economic allocation for refining processes is used in this study and discussed in Section 4.3.6. There are no appropriate physical relationships that can be found between the co-products in a refinery, so ISO 14044 recommends using a relative value such as market value (ISO, 2006). For example, density cannot be used as an allocation parameter because adjusting the mass or volume of asphalt output in the refinery complex does not cause a predictable, related perturbation in the energy consumption of the refinery. The refining processes are too complex, as co-products are outputted at different stages in the refinery and producing one product instead of another requires significant upgrading or other extra procedures. In terms of using energy content as an allocation parameter, asphalt binder is not used as a fuel like many other petroleum products, so its embodied energy will not serve as a motivation to produce more or less of the product (Blomberg et al., 2011).

However, it is possible to use physical parameters to perform allocations for refining, and the effect of using different allocations was studied in a sensitivity analysis. Using a similar approach as that described in Section 4.3.6, the allocation coefficients were calculated and Table 4.17 gives the corresponding allocation factors when using mass, volume, and energy content as allocation parameters.

Table 4.17 Allocation Factors for Various Refining Allocations for Each PADD

Allocation	**PADD1**	**PADD2**	**PADD3**	**PADD4**	**PADD5**	**U.S.**
Mass	1.00	1.00	1.00	1.00	1.00	1.00
Volume	0.76	0.75	0.74	0.75	0.75	0.75
Energy Content	0.89	0.89	0.89	0.89	0.87	0.89
Market Value	0.42	0.42	0.42	0.37	0.45	0.50

Compared to the market value allocations, the mass, volume, and energy content allocations will attribute more process energy to asphalt binder during refining. The range of total life cycle energies for binder using different allocations is presented in Figure 4.9. The effect of using a mass allocation over an economic allocation is an increase in energy of between 47–76% of the total life cycle depending on the PADD. The effect if using a volume allocation or energy allocation would be an increase in energy of 25–46% and 39–63%, respectively.

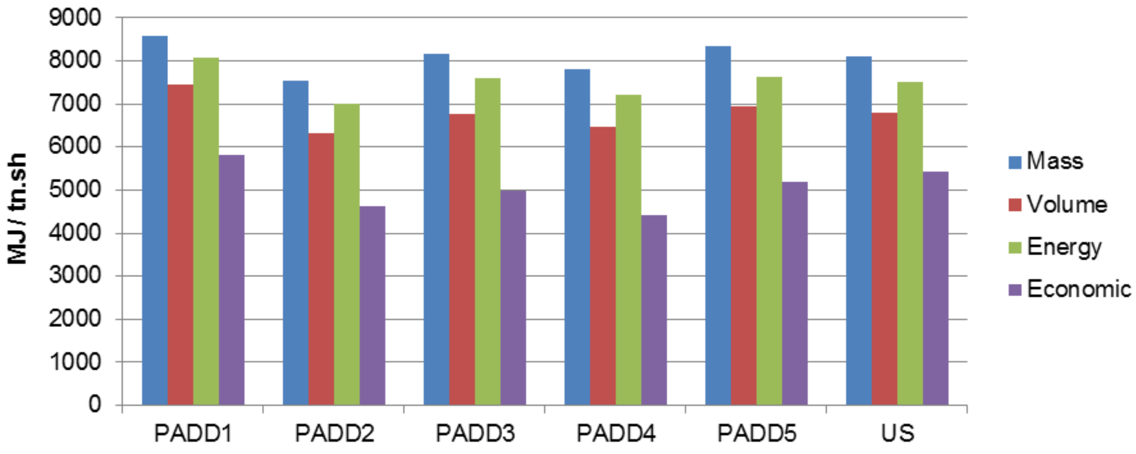


Figure 4.9 Energy consumption for binder production with various allocations.

4.4.3 Feedstock

ISO 14044 defines feedstock energy as the “heat of combustion of a raw material input that is not used as an energy source to a product system” (ISO, 2006). There is ongoing debate as whether or not to include the feedstock energy of binder in life cycle assessment and how to count its impact. For example, in a recent work, (Butt et al., 2014) argues that the feedstock energy of binder is only relevant if it is combusted or it can disregarded and considered to have been “borrowed” from nature. Santero (2009) has also written about this topic and specifically on the low process energy that would be needed to convert binder into a more usable a fuel as well as the emissions it would produce upon combustion. He concludes that it does not seem reasonable to exclude feedstock energy from the LCA.

In this study, the feedstock is accounted for, but reported separately from the rest of the LCA. Thus, all of the results in this chapter have not included the feedstock energy. The feedstock energy is taken to be 40.2 MJ/kg and is constant for all PADDs (Garg et al., 2006). A graph showing the contribution of feedstock among the other stages of the binder life cycle are shown in Figure 4.10. The embodied energy is approximately 6.3–8.2 times the process energy for the PADDs.

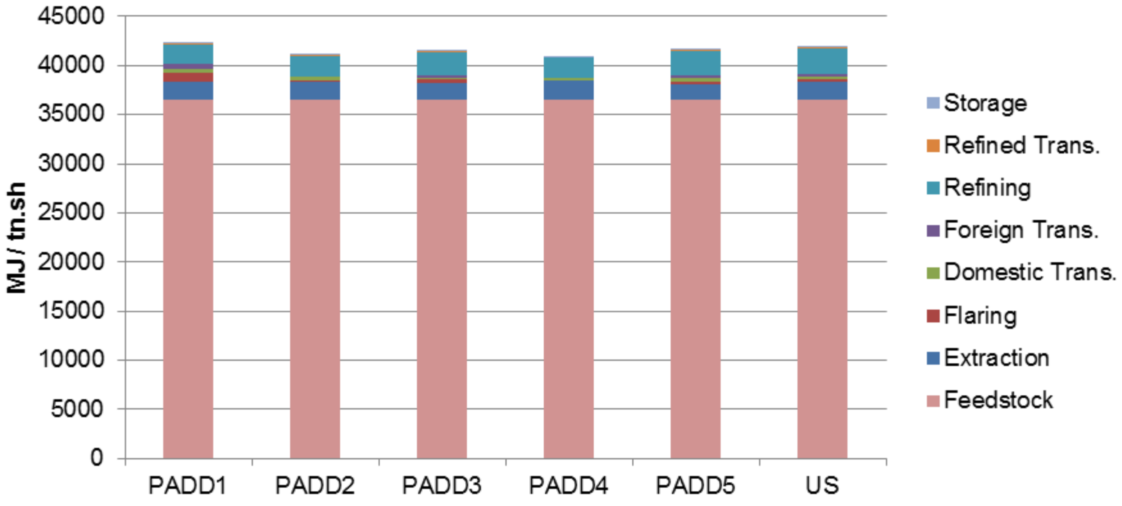
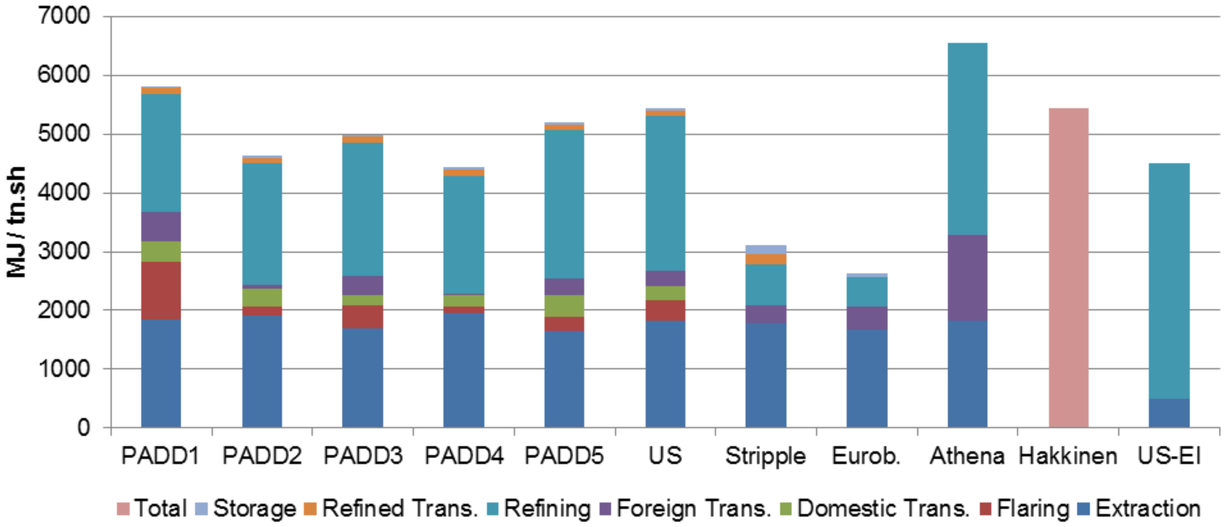


Figure 4.10 Energy consumption for binder production with feedstock energy.

4.4.4 Validation

The final step in developing a LCA framework for asphalt binder production is to compare the results from the model with those found in published literature. The four main sources of literature regarding the impacts of producing asphalt binder are from Stripple (2001), Eurobitume (Blomberg et al., 2011), Athena (2001), and Häkkinen and Mäkelä (1996). These sources were described in the literature review (Section 2.2.2) and were chosen because, with the exception of the last source, they give detailed explanations of the calculations used to determine the life cycle energy and GWP impacts. The disaggregated results are shown in Figure 4.11, along with a default process for *Bitumen, at refinery/US-US-EI* from US-EI 2.2.



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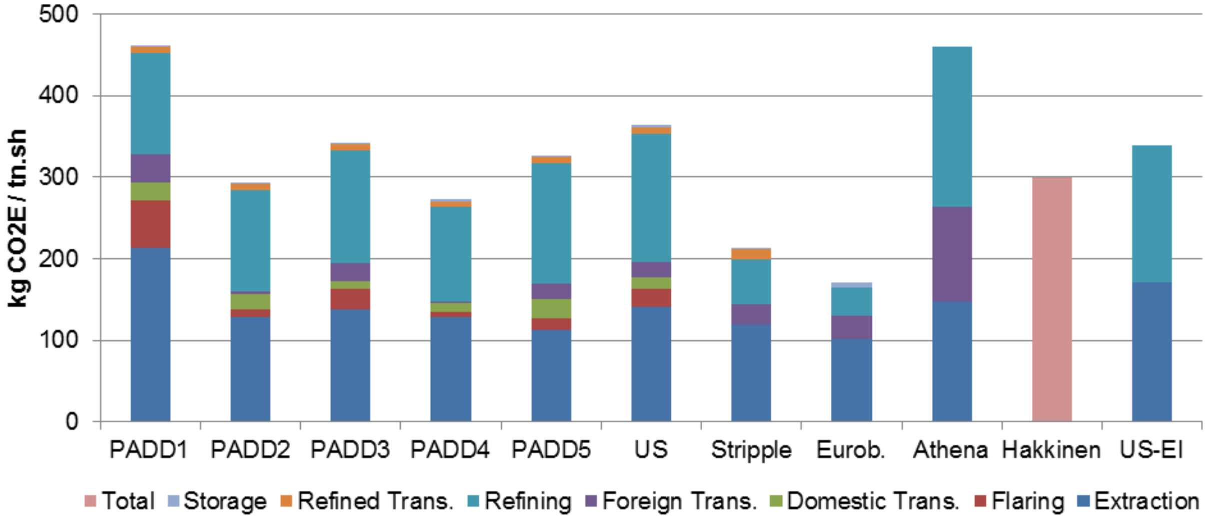

(b)

Figure 4.11 (a) Energy and (b) GWP comparisons of literature values with binder model.

The values for both energy consumption and GHG emissions are comparable for the literature sources and for the models developed in this study. However, the range of values is large and there are a few reasons to explain this discrepancy. First, the system boundaries are not the same for all of the studies. Indirect energy from fuel production using the GREET model was added to the Athena and Stripple models to make them comparable with the other sources. The foreign and domestic transportation for the published sources are not distinguished and have been grouped under foreign transportation. The flaring is also not separately reported and is assumed to be grouped with crude extraction and production. In addition, while Stripple reports refines transportation and storage; Eurobitume, Athena, and US-EI 2.2 do not. There are no details reported by Häkkinen and Makelä (1996).

Second, the sources also represent different time periods and geographic regions. Häkkinen and Makelä include results from the early 1990's representing processes in Finland, while Stripple first published results in 1995 with values from Sweden. The report by Eurobitume is based on data from 2009 and 2010, with emissions data coming from reports by the OGP, the Association for the Conservation of Clean Air and Water in Europe (CONCAWE), as well as Ecoinvent 2.2. Information about the distribution of crude sources, energy consumption, and transportation came from questionnaires given to Eurobitume members. Thus, the results from Eurobitume are fairly up-to-date but also Eurocentric. The US-EI 2.2 data similarly represents European data, modified for U.S. electricity, and is based on data from 2000. The results from Athena's LCI were compiled using data from 1993-1999, mostly consisting of proprietary data from Franklin Associates as well as SimaPro 5, with data mostly representing the U.S.

Third, the refining processes seem to have the largest variances among the sources. This can be partially attributed to the different allocations used by each sources: mass allocation by Stripple, Athena, and US-EI 2.2 but economic allocation by Eurobitume and the model from this study. From the sensitivity study performed in Section 4.4.2.2, it was found that the type of allocation used can cause up to a 76% difference in the total energy consumption of the entire life cycle. In addition, the high intensity energy consumption in U.S. refineries may be a result of the large percentage of heavy crudes from Canada and Venezuela that are processed in the U.S. The refining process reported by Athena also has a high energy requirement, though, surprisingly, crude extraction from the same source has a relatively low impact and do not seem to consider Canadian oil sands.

Finally, a literature report conducted by Zapata and Gambatese (2005) found energy consumption in the range of 381–5443 MJ/tn.sh binder from four different studies[17] at the time of publication. Thus, it is clear that there is a wide range of energy and GWP values for binder production in literature. While the life cycle impacts of binder production in the U.S. seem to be relatively high compared to other literature sources, the discrepancies may be explained by, for example, the system boundaries (to terminal storage rather than just refinery), the high proportion of heavy crudes that are processed in U.S. refineries, the

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[17] Two of these studies are Stripple (2001) and Häkkinen & Mäkelä (1996).

type of allocation used, and finally the diversity in global crude sources and reliance on overseas transportation.

4.5 Summary

A summary of key assumptions and sources used in the life cycle framework for asphalt binder production is included in Table 4.18.

Table 4.18 Summary of Major Assumptions and Sources Used in the Binder Model

Stage	Source	Major Assumptions and Limitations
Crude Extraction	EIA PSA	• Average EIA PSA data from 2005-2012 was used • North American crude production was used as a proxy for South American crude production • Effect of using Canadian oil sands was not considered • Countries importing less than 0.5% crude were excluded
Crude Flaring	NOAA	• Sweet and sour flaring was distinguished
Crude Transportation	EIA PSA, calculators	• Land transportation done via pipeline • Overseas transportation done via oil tanker
Refining	EIA PSA, SCQAMD, EIA SEDS	• Refinery flares were extrapolated from California data • Externally purchased hydrogen was not considered • Fuel combustion shares adapted from GREET • Effects of crude quality on refining processes were not considered
Refined Transportation	MOVES	• Transportation done via hauling truck (not heated)
Blending and Storage	Heatac, NCDAQ	• Foreign refined product imported to storage was not considered • Emissions from blending and storage were not included

5 Case Study – Flexible Pavement Project

In this chapter, a case study of a flexible pavement reconstruction and its remaining life cycle will be examined using the LCA framework developed in Chapter 0. Major assumptions and results for each of the five phases are discussed, followed by a summary of the significant findings. In addition, two alternative scenarios are presented that take into consideration different PADDs for asphalt binder and different landfilling percentages in the EOL phase.

5.1 Background

As part of the Illinois Tollway's 2004 Congestion Relief plan, the agency authorized a $200 million project to reconstruct 14.3 miles of the Jane Addams Memorial Tollway (I-90) between Newburg Road and Rockton Road from mileposts (MP) 2.7 to 17.0 (ISTHA, 2011). The construction occurred between 2008–2009 for both eastbound and westbound sections and a lane was added to both directions to increase the traffic capacity from four to six lanes. The project benefits included congestion relief and improved safety and mobility as well as prolonged service life for the roadway. The average daily traffic (ADT) for the section was approximately 66,000 vehicles in 2008.

The case study in this thesis focuses on the eastbound reconstruction and future maintenance for the 4.98-mi pavement section between Illinois Route 173 to Rockton Road (MP 3.93 to 8.91). Data concerning the actual mix designs used in the reconstruction, the predicted 60-year maintenance schedule, and the traffic conditions were obtained from the Illinois Tollway with assistance from Applied Research Associates, Inc. The functional unit for this study is one pavement project of a high volume urban restricted highway over a 60-year analysis period under the jurisdiction of the Illinois Tollway.

The goal of this study is to implement the complete, regional LCA framework described in the earlier chapters of this thesis in a realistic application. In addition, the two alternative scenarios presented at the end of the case study will function as a limited sensitivity analysis that considers the effects of using different assumptions. The scope of the project includes all five phases of the LCA, including material production, construction, maintenance, use, and EOL.

5.2 Material Production Phase

The system boundaries of the material production phase include the mainline, paved shoulders, and bases of the reconstruction, excluding seal, tack and prime coats. The unpaved shoulders as well as any drainage components (e.g. underdrains) and structural components (e.g. median barriers, lighting, etc.) are not considered. Slope is not considered, so all pavement elements are approximated to be rectangular as shown by the cross-section in Figure 5.1. The main layers are full-depth HMA (FDHMA), aggregate capping course (Agg. Cap), and porous granular embankment (PGE).

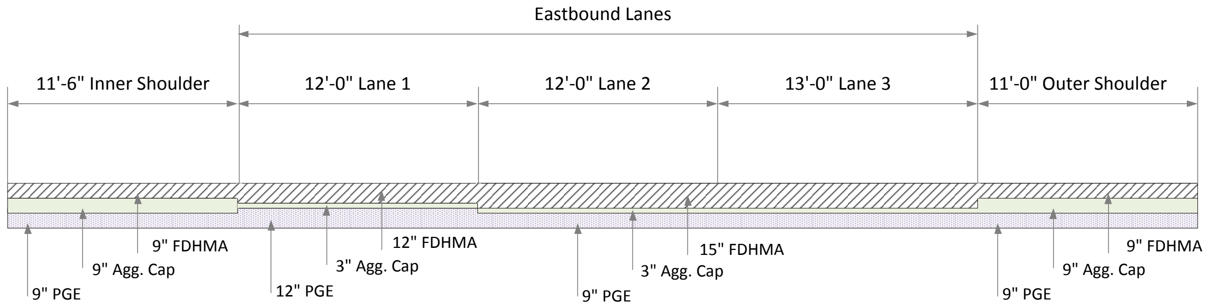
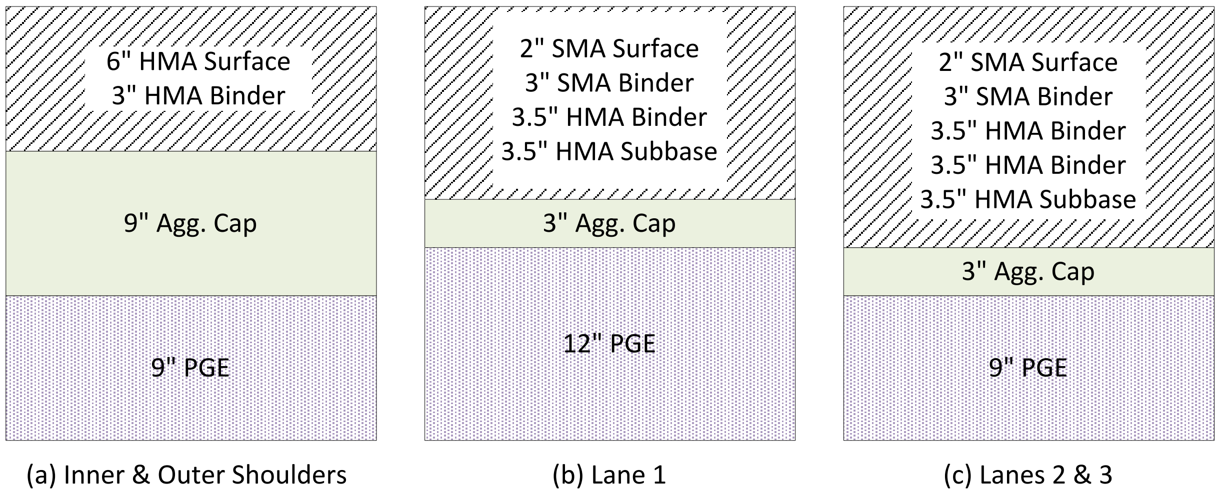


Figure 5.1 Cross-section of the simplified pavement structure used in the case study.

A cross-section of the layers in the pavement structure for each lane and shoulder is given in Figure 5.2. Note that the FDHMA for lane 1 is 12-in thick while the FDHMA for lanes 2 and 3 are 15-in thick.



(a) Inner & Outer Shoulders (b) Lane 1 (c) Lanes 2 & 3

Figure 5.2 Cross-section of the pavement layers for (a) inner and outer shoulders, (b) lane 1, and (c) lanes 2 and 3.

5.2.1 Assumptions

A total of 15 mix designs are considered throughout the project length. The 13 asphaltic mixtures represent 91% of the total tonnage actually used in the 2008 project. A summary of the mix types and usage are given in Table 5.1. The transportation of materials to HMA plants and from HMA plant to construction site is based on actual distances between Illinois quarries and plants.

Table 5.1 Summary of Mix Designs in Case Study

No.	Type	Description	Thickness in	RAP content %	Tonnage % Project	Lanes		
						1	2	3
Mainline FDHMA								
1	SMA Surface A	GTR	2	15	3.4	X	X	X
2	SMA Surface B	GTR	2	15	3.6	X	X	X
3	SMA Surface C	GTR	2	15	3.0	X	X	X
4	SMA Binder A	GTR	3	15	10.8	X	X	X
5	SMA Binder B	GTR	3	15	5.1	X	X	X
6	HMA Binder A	N70, 19.0 mm	3.5	35	3.8	X	X	X
7	HMA Binder B	N70, 19.0 mm	3.5	40	7.8	X	X	X
8	HMA Binder C	N90, 19.0 mm	3.5	20	11.6	X	X	X
9	HMA Binder D	N90, 19.0 mm	3.5	20	5.2	X	X	X
10	HMA Subbase A	N50, 19.0 mm	3	50	18.1	X	X	X
11	HMA Subbase B	N50, 19.0 mm	3.5	50	8.9	X	X	X
Shoulder FDMA								
12	HMA Surface	N70, 9.5 mm	6	25	3.7		---	
13	HMA Binder	N50, 19.0 mm	3	40	5.7		---	
Base								
14	Aggregate Capping Course		3 or 9	---	---		---	
15	Porous Granular Embankment		9 or 12	---	---		---	

5.2.2 Results

The total energy consumption and GWP for material production for each layer per lane-mile are shown in Figure 5.3. The abbreviations are defined as SC for surface course, BC for binder course, and SB for subbase. The energy and GWP broken down by material is shown Figure 5.4, and complete results for each mix can be found in Appendix B.

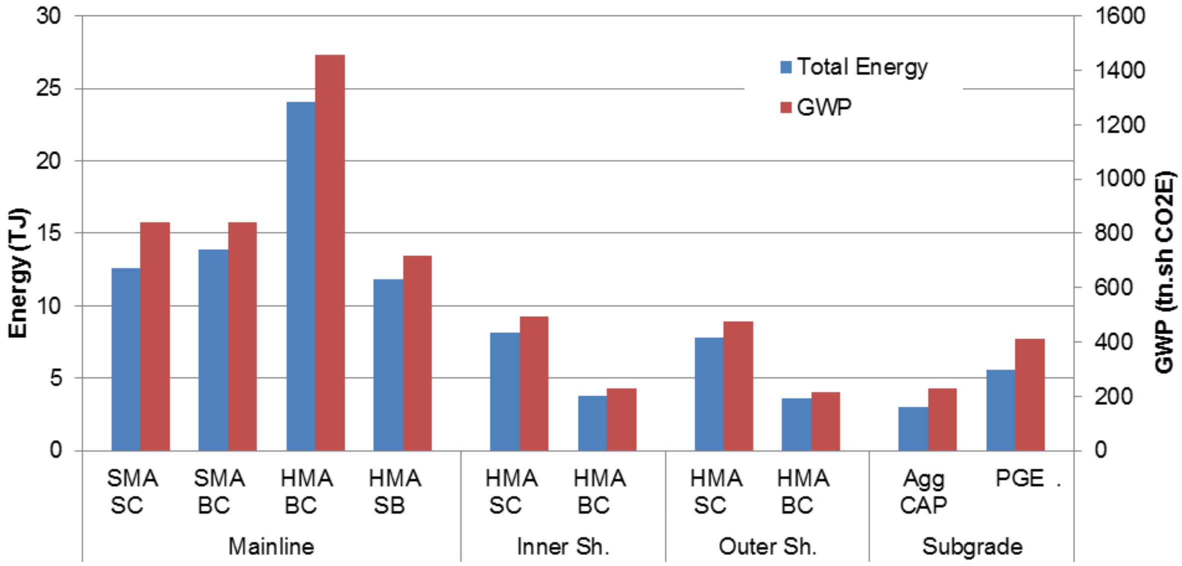
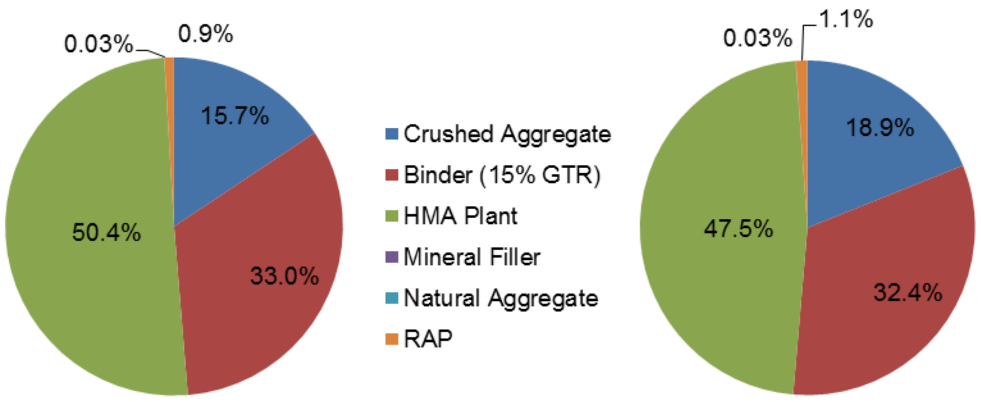


Figure 5.3 Total energy and GWP impacts for the material phase by layer.



(a) (b)

Figure 5.4 (a) Energy and (b) GWP for each material production.

From Figure 5.3, the energy and GWP are largest for the mainline, due to volume as well as processes involved, specifically the asphalt binder and HMA plant operations. Thus, the per unit environmental burdens of PGE are very small compared to the mainline layers, considering that the PGE is 9 or 12-in and each mainline layer is between 2 to 3.5-in. The HMA binder course is particularly high in the mainline because lane 2 and 3 include an extra 3.5-in layer of binder. In Figure 5.4, HMA plant operations account for approximately half of the total energy and GWP in the material phase, while asphalt binder production contributes approximately one-third of the reported environmental burdens. The contribution of crushed aggregate is also quite high because the tonnage of aggregate in the HMA mixtures and also the underlying aggregate layers is very large.

5.3 Construction Phase

The construction activities considered in this study include hauling of materials from plant to site, excavation, and the construction of each pavement component: aggregate base, porous granular embankment, FDHMA for mainline, and HMA courses for shoulders. The haul distances were taken from actual project records and averaged approximately 20 miles. The transportation of equipment to site was not considered at this point. The excavation amount was also taken from Illinois Tollway records, but the hauling of the excavated material was not considered. A summary of the activities considered in initial construction are in Table 5.2.

Table 5.2 Summary of Initial Construction Activities

Task	Amount	Unit
Hauling of materials to site	2,885,457	tn.sh-miles
Excavation	1199814	CY
Construction of PGE	46380	CY
Construction of Aggregate CAP	155277	tn.sh
Construction of FDHMA (mainline)	42120	CY
Construction of HMA SC/BC (shoulders)	33892	tn.sh

5.3.1 Results

The total energy and GWP for the construction phase by task is shown in Figure 5.5 and by equipment in Figure 5.6. The environmental burdens of each task is calculated based on fuel consumption, whose combustion is modeled differently for different equipment types and horsepower based on EPA's NONROAD software. The excavation activity is by far the most fuel-consuming task; it requires dozers, loaders, rollers, and trucks, which correspondingly have high contributions in Figure 5.6. The asphalt paving tasks have the lowest energy and GWP contribution.

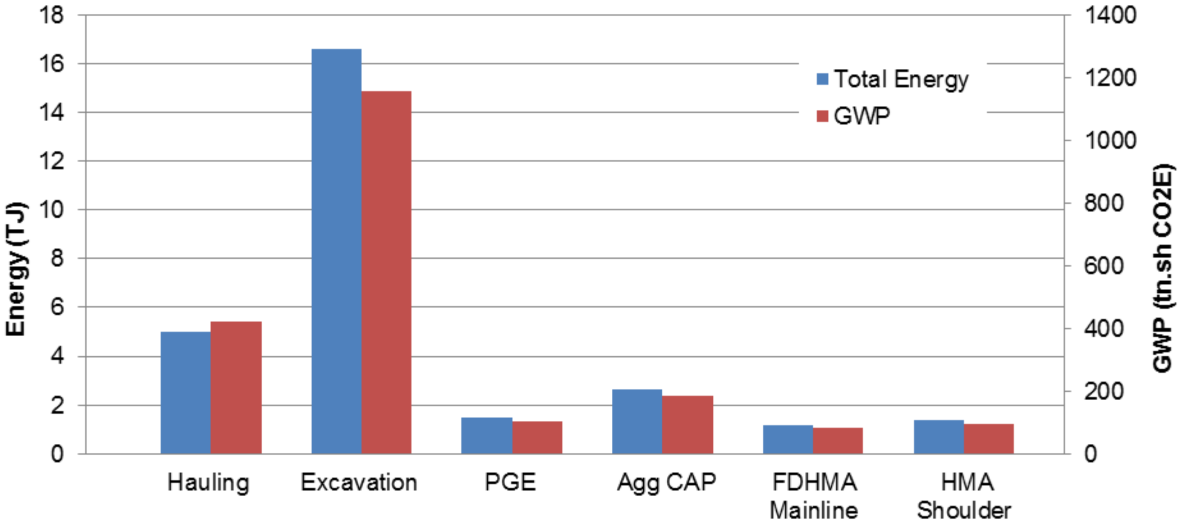
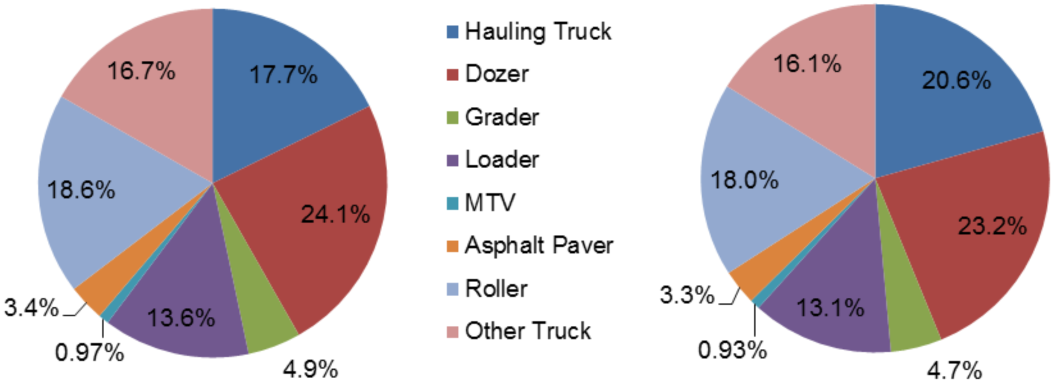


Figure 5.5 Total energy and GWP impacts for the construction phase by task.



(a) (b)

Figure 5.6 (a) Energy and (b) GWP for each equipment for the construction phase.

5.4 Maintenance Phase

The maintenance schedule for a typical FDHMA pavement is projected to 60 years by the Illinois Tollway. The maintenance activities in Table 5.3 are followed in the case study.

Table 5.3 Typical FDHMA Maintenance Schedule

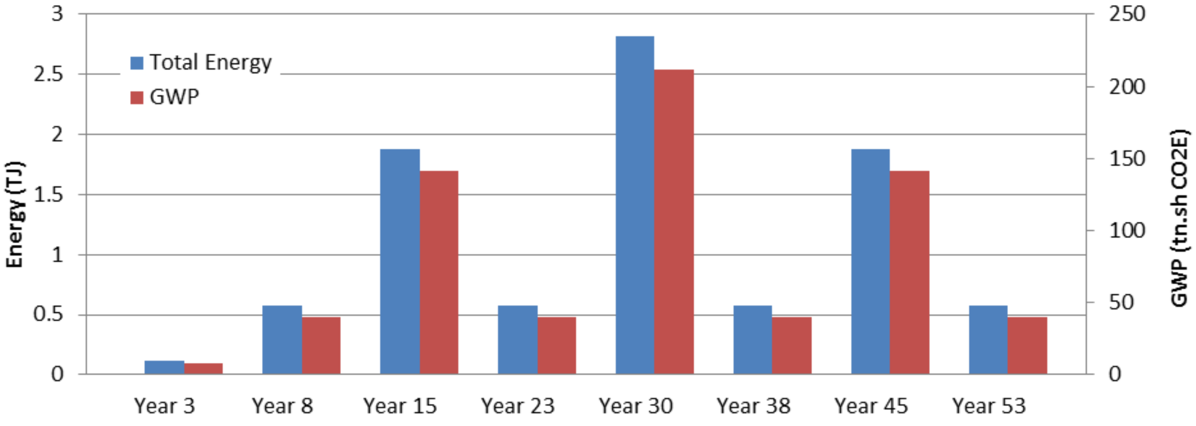
	Year:	0	3	8	15	23	30	38	45	53	60
Mainline											
Rout & Seal	% length	Reconstruct	100	150		150		150		150	EOL
Patch	% area			0.3	1.0	0.3	1.0	0.3	1.0	0.3	
Mill	in				2		4		2		
HMA Overlay	in				2		4		2		
Shoulder											
Rout & Seal	% length	Reconstruct		400		400		400		400	EOL
Patch	% area				2.0		2.0		2.0		
Mill	in				2		2		2		
HMA Inlay	in				2		2		2		
Microsurface	Y/N			Y		Y		Y		Y	

5.4.1 Assumptions

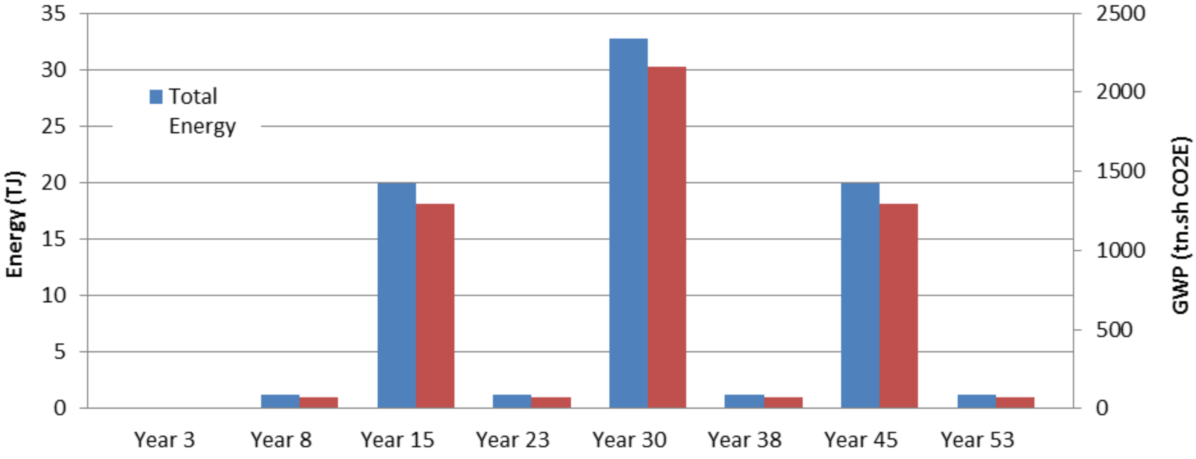
The actual mixes used in patching and HMA overlays or inlays were not available. Thus, it was assumed that the mix designs from the surface courses in initial construction were used for these materials. The patches were assumed to be full-depth patches, going to a depth of 12-in. The sealant material was used directly from the inventory database and transported 25 miles, while the surfacing material was assumed to have a composition of 0.75 gal/SY of asphalt emulsion and 20 lb/SY crushed aggregate, both materials being transported 30 miles.

5.4.2 Results

The results for the maintenance phase are reported separately for construction activities and material production needed for maintenance, as shown in Figure 5.7. Detailed results for the maintenance phase can be found in Appendix B. The environmental burdens of material production is roughly 10 times that for construction activity. This is a similar trend between the material production phase and the construction phase. The years with the highest energy and GWP are those that involve HMA overlays.



(a)



(b)

Figure 5.7 Energy and GWP impacts for the maintenance (a) activities and (b) materials by year.

5.5 Use Phase

The use phase in this case study includes only the components of pavement albedo and roughness due to IRI. Carbonation is not applicable to flexible pavement and the effects of leachate are generally negligible, as discussed in Section 3.5.

5.5.1 Albedo

In terms of albedo, it was found that both the urban heat island effect and the radiative forcing effect are negligible in this study. The section of pavement included in this case study passes through the edge of Roscoe and Rockton, Illinois (see Figure 5.8). The urban heat island effect is significant for congested urban areas, so it is not applicable to this case study.

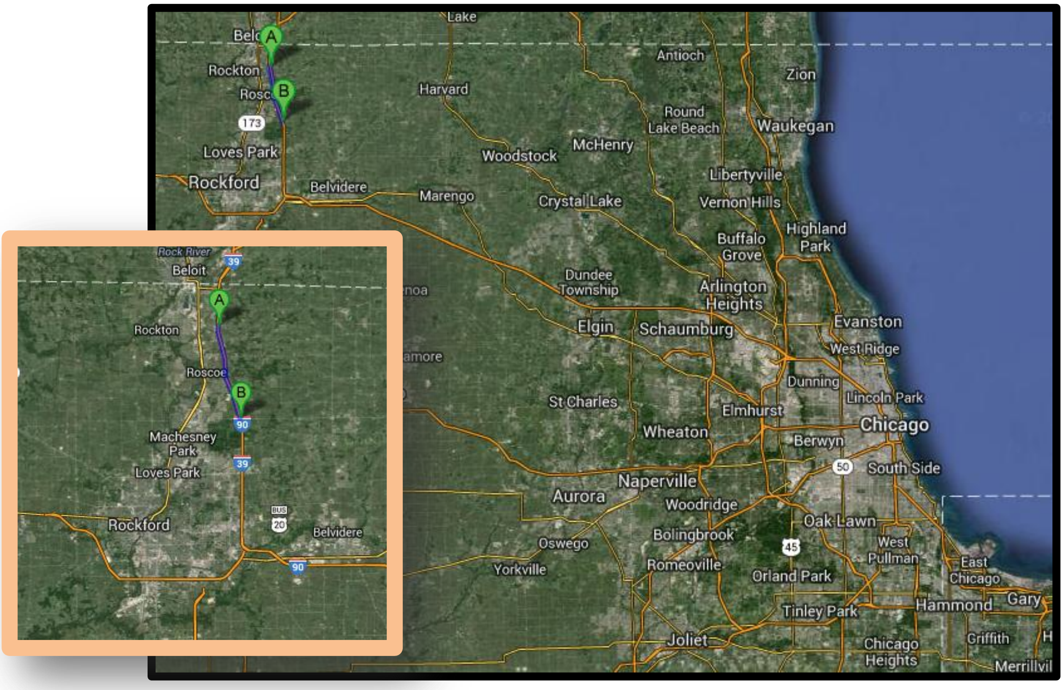


Figure 5.8 Location of I-90 section for case study (inset: close up of section).

A change in radiative forcing is only appropriate when the surface albedo increases or decreases. This usually happens during a maintenance or rehabilitation cycle. While the case study does include a number of overlays and microsurfacings, there is insufficient information to predict the condition of the surface before and after rehabilitation. Future work can be done on this subject to find the net change in albedo for the entire maintenance schedule. For now, a simple calculation in Equation 5.1 is done for a 0.1 increase in albedo (i.e. the difference between a weathered and a new HMA overlay (Pomerantz et al., 1997)) to see the contribution of a positive change in radiative forcing to the use phase.

$$GWP = \Delta B \times A \times \left(\frac{2.55\ kg\ CO_2E}{0.1\ m^2 \times 0.01\ change\ in\ albedo}\right) \quad \textbf{Equation 5.1}$$

$$= 0.1 \times (90385m^2) \times \left(\frac{2.55\ kg\ CO_2E}{0.1\ m^2 \times 0.01}\right) \times \left(\frac{1\ tonne}{1000\ kg}\right) = 2{,}305\ tonne\ CO_2E$$

The uncertainty of this result is large; however, compared to GWP impacts found in the following section, the estimated contribution of radiative forcing for a 0.1 decrease in albedo is approximately 70 times less than the contribution of extra fuel consumption due to roughness. This supports the assumption that the effects of albedo on the pavement life cycle can be neglected for this case study.

5.5.2 Roughness

In order to predict the roughness progression of the pavement over time, IRI data from 2000–2005 for the exact section were fitted with a linear regression. The data were inconsistent between MP 4.0 and MP 9.0, and a weighted average was used to extrapolate a simple linear IRI progression for the section. Equation 3.1 is used, where *t* is the age of the pavement.

$$IRI(t) = IRI_0 + 3.5t \quad \textbf{Equation 5.2}$$

Furthermore, using historical data from the Illinois Tollway, it was estimated that the IRI would drop by 30 in/mi with a 2-in HMA overlay and 40 in/mi with a 4-in HMA overlay. No reasonable relationship between minor maintenance or repairs could be found in the historical data, so the effect of maintenance activities (e.g. patching, sealing cracks, etc.) on roughness was not considered. It was also gathered from historical data that 70 in/mi is an appropriate assumption for the initial IRI after reconstruction. The IRI progression curve for the section is shown in Figure 5.9 with the baseline IRI set to 64 in/mi[18].

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[18] From Chatti and Zaabar (2012).

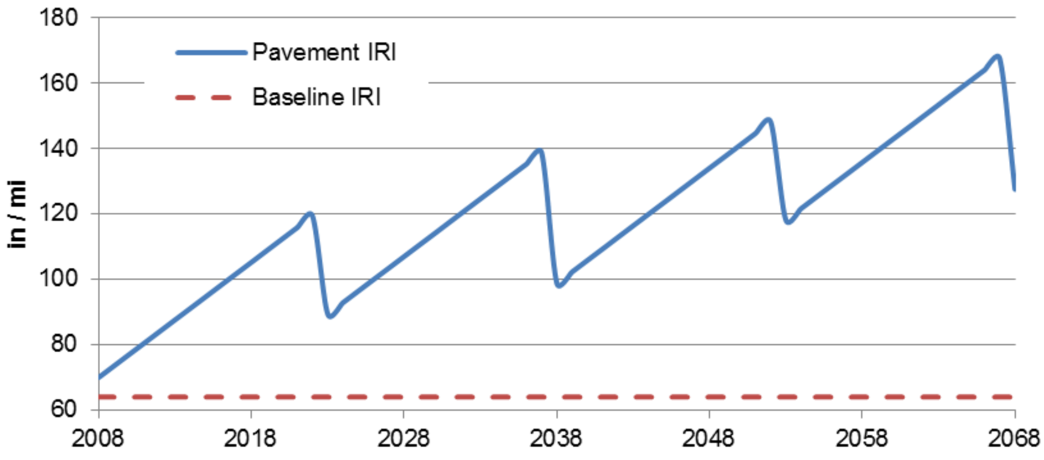


Figure 5.9 Predicted IRI progression from 2008-2068.

The ADT during construction year was assumed to be 66,000 from Illinois Tollway data. Passenger vehicles make up 88.7% of the traffic, while multiple unit vehicle make up 11.3%. A growth rate of 1.97% is assumed.

5.5.3 Results

The extra fuel consumption, as shown in Figure 5.10, closely follows the trend of the IRI progression in Figure 5.9. Multiple unit vehicles account for approximately half of the extra fuel consumption as compared to passenger vehicles. Although multiple unit vehicles require higher fuel consumption, these larger vehicles only encompass 11.3% of the total ADT.

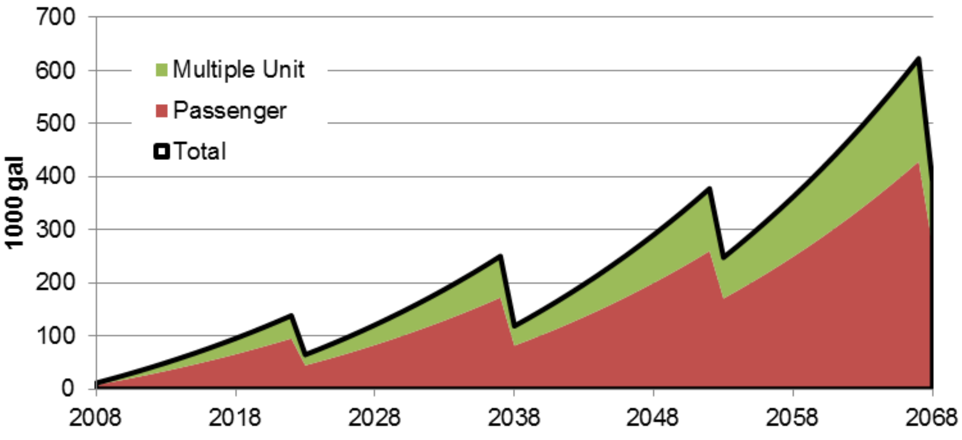


Figure 5.10 Extra fuel consumption of passenger and multiple unit vehicles by year due to change in IRI in the use phase.

The energy consumed, GHG emitted, extra VMT, and extra gals of fuel accumulated during the use phase are shown in Table 5.4. Clearly, the impacts from multiple unit vehicles are much greater per vehicle that than of passenger vehicles. While the extra VMT for multiple unit vehicles is approximately 10% of passenger vehicles, the energy and GWP is closer to 40–50%. Thus, on a road with heavy truck traffic, the change in IRI roughness on vehicle fuel efficiency could have much more significant environmental impact than the 11.3% trucked road considered in the case study.

Table 5.4 Energy and GWP from Passenger and Multiple Unit Vehicles in the Use Phase

Vehicle Type	**Energy GJ**	**GWP tn.sh CO_2E**	**Extra Mileage mil VMT**	**Extra Fuel mil gal**
Passenger	1,614	109,907	294	9.55
Multiple Unit	611	51,406	22	4.32
Total	**2,224**	**161,313**	**316**	**13.87**

In addition, there are some limitations in regards to the predicted vehicle mix considered in this simplistic evaluation of the use phase. The predicted vehicle mix is the same as is the average vehicle operating processes chosen to represent these vehicles. However, with the increasing popularity of hybrid cars and more energy-efficient vehicles in the U.S., the extra fuel consumption from extra VMT in future years should decrease. Thus, it is expected that this case study overestimates the environmental impacts from the use phase.

5.6 End-Of-Life Phase

A hypothetical scenario was used for the EOL of the pavement, where the entire HMA upper bound layers from the pavement structure for the mainline and shoulder are removed. This is assumed to occur in Year 60, seven years after the last maintenance activity. It is also assumed that the entire depth of the HMA pavement for the mainline and shoulders are milled, removed, and hauled approximately 20 miles. No consideration to in-place recycling or landfilling is given because it is simplistically assumed that the removed pavement will be processed at a plant to make RAP. The cut-off approach is used, so the burdens for the removal and transportation are attributed to the existing pavement in the case study. Accordingly, the system boundary of the RAP material used in the material production phase begins with broken pavement at the plant site.

5.6.1 Results

The results of the EOL phase are given in Figure 5.11 and Figure 5.12. The removal of the mainline pavement requires more energy and emits more GWP due to the volume entailed, but hauling invokes an environmental burden approximately 4.0 times that of removal.

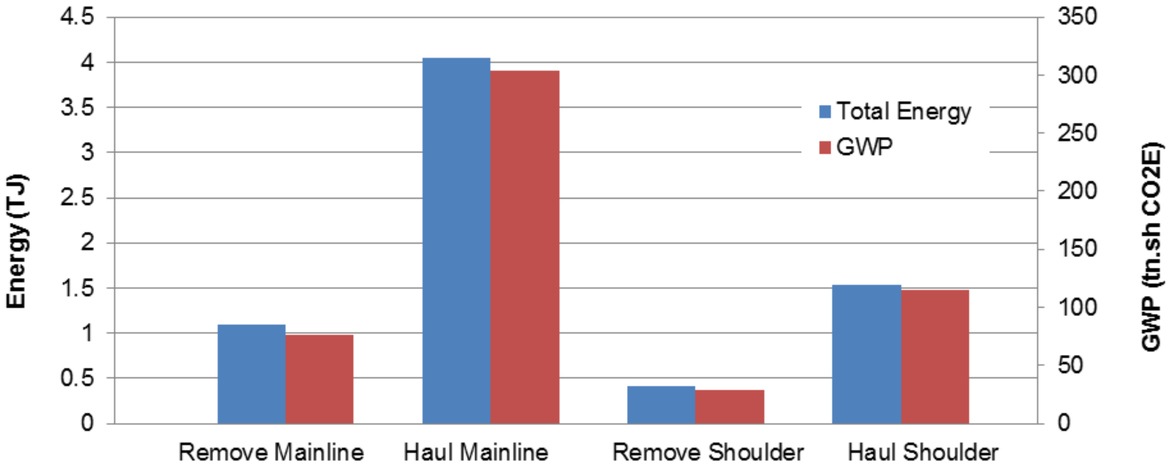
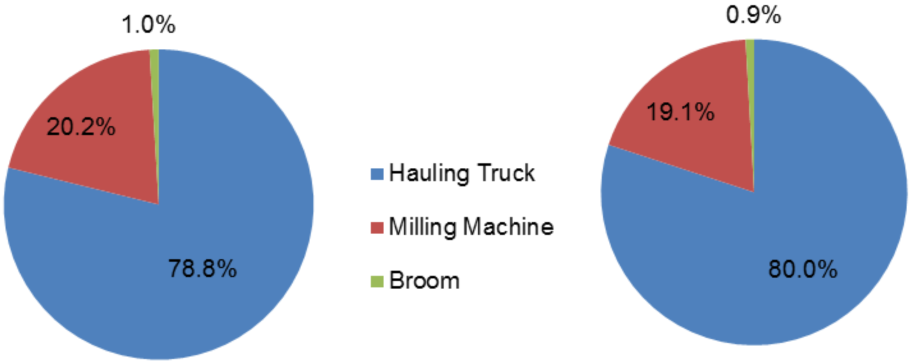


Figure 5.11 Total energy and GWP impacts for the EOL phase.



(a) (b)

Figure 5.12 (a) Energy and (b) GWP for each equipment using in the EOL phase.

5.7 Summary of Results

A summary of the transportation of material to and from construction site, material production tonnage, and fuel consumption is given in Table 5.5. The quantities provide a cursory logical check for the analysis to ensure that the data processed for each phase is reasonable.

Table 5.5 Summary of Transportation, Tonnage, and Fuel Usage for Each Phase

Phase	Transportation tn.sh-mi	Material tn.sh	Equipment Fuel gal	Vehicle/Truck Fuel gal
Material Production	5,390,105	397,766	-	35,036
Construction	2,885,457	-	136,367	18,755
Maintenance	2,021,502	80,160	55,367	13,140
Use	-	-	-	13,866,513
End-of-Life	2,821,946	-	8,786	18,343
Total	**13,119,010**	**477,926**	**200,520**	**13,951,787**

A summary of the energy and GWP for each phase is given in Figure 5.13 in logarithmic scale, with the percent contribution for each phase displayed above each bar. Not surprisingly, the use phase is responsible for more than 90% of the energy and GHG emissions. The EOL phase accounts for the least, while phases involving material processing (material production and maintenance phase) have similar environmental burdens.

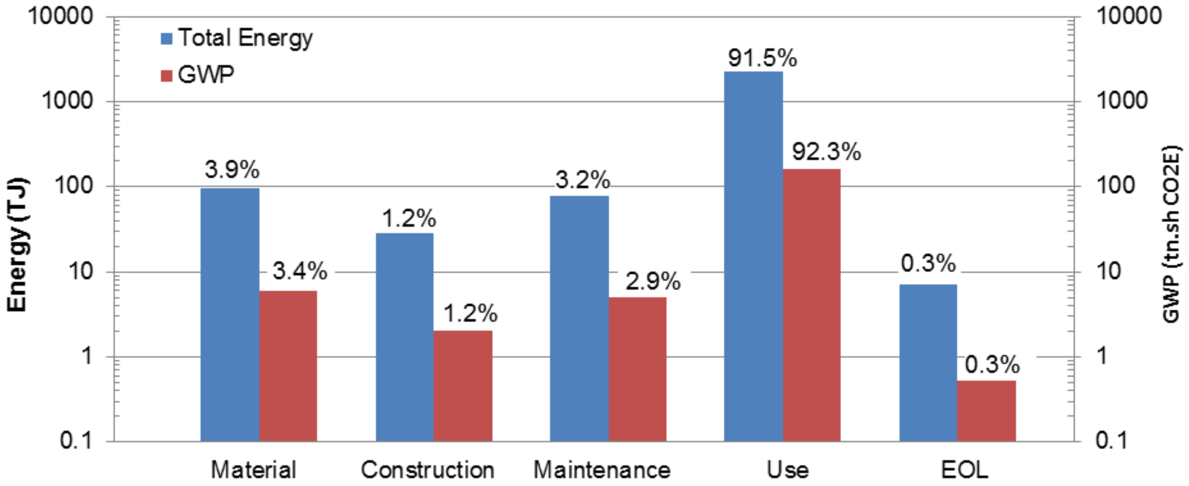


Figure 5.13 Energy and GWP for each phase in the life cycle.

When the feedstock energy of asphalt binder is included in total energy (Figure 5.14), the energy contributions from the material production and maintenance phases increase by approximately 5%, but the use phase still contributes more than 80% of the total energy of the life cycle.

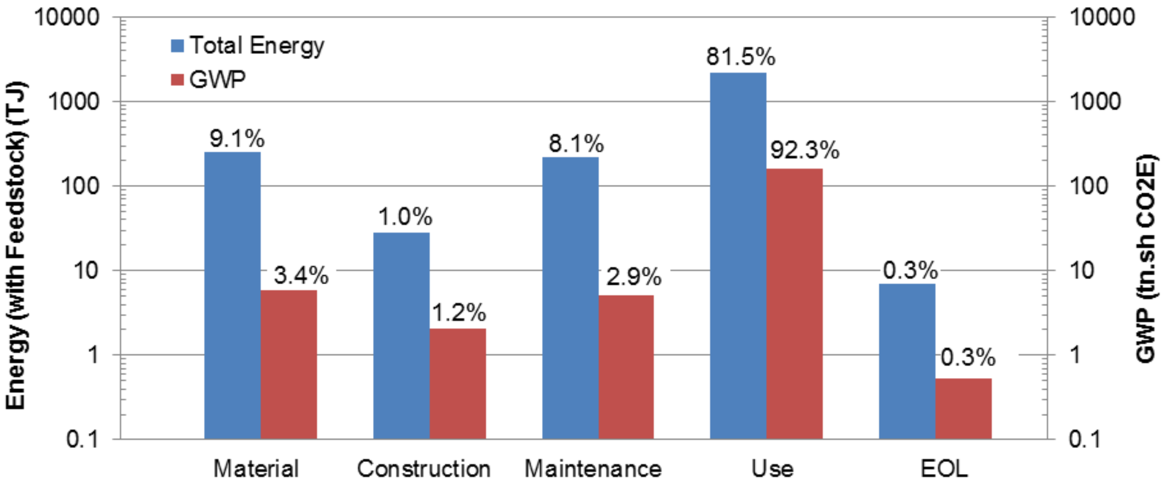


Figure 5.14 Energy (with feedstock energy) and GWP for each phase in the life cycle.

A full summary of all 12 TRACI impacts are given in Figure 5.15 on the following page, while the numerical results can be found in Appendix A.

A similar trend is followed for ozone depletion, smog, acidification, eutrophication, and fossil fuel depletion. Respiratory effects have a slightly higher impact for the material and maintenance phases mainly due to particulates released during aggregate production, but the use phase maintains its position as the highest contributing phase. Carcinogenics and non-carcinogenics are emitted in large quantities during asphalt binder production, which causes increased contributions from the material production and maintenance phases. Thus, the carcinogenic and non-carcinogenic impacts from the material production are approximately twice that of the use phase, while those same impacts from the maintenance phase are approximately half that of the use phase. Finally, the ecotoxicity burden for the material production, maintenance, and use phases are all similar. This is due to the large ecotoxicity contribution from asphalt binder production.

In LCA practice, the impact assessment can include an optional normalization and weighting step to obtain a single score for the product that takes into consideration multiple impact categories (ISO, 2006). However, the use of normalization and weighting is not yet established in the LCA field, so this project does not consider a single score. In any case, it is evident from the results of this case study in Figure 5.15 that total energy and GWP do not necessarily represent the trend taken for all environmental impacts with respect to the five phases of the pavement life cycle.

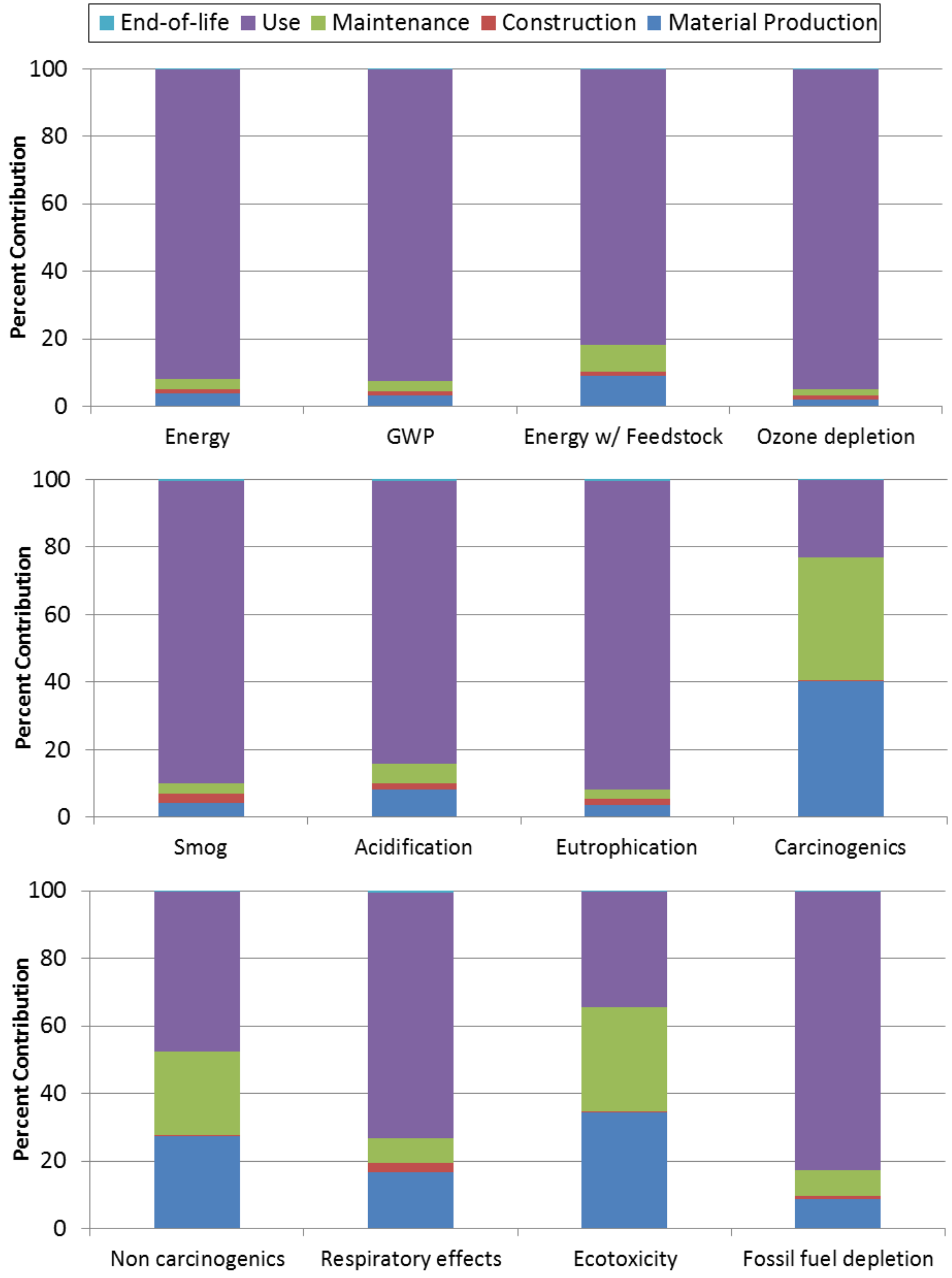
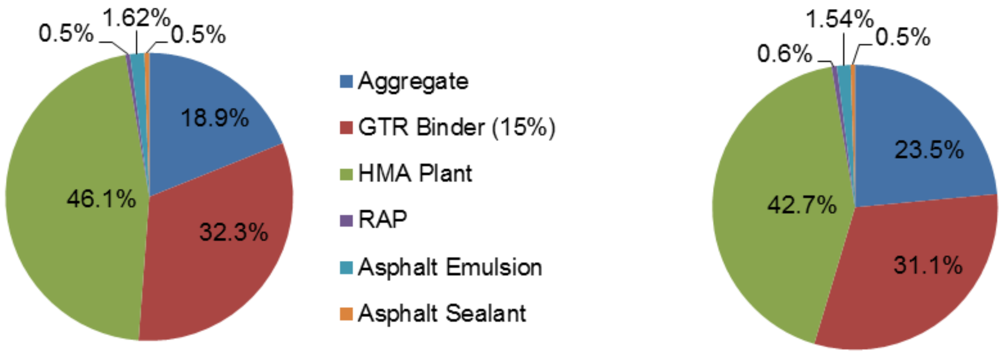


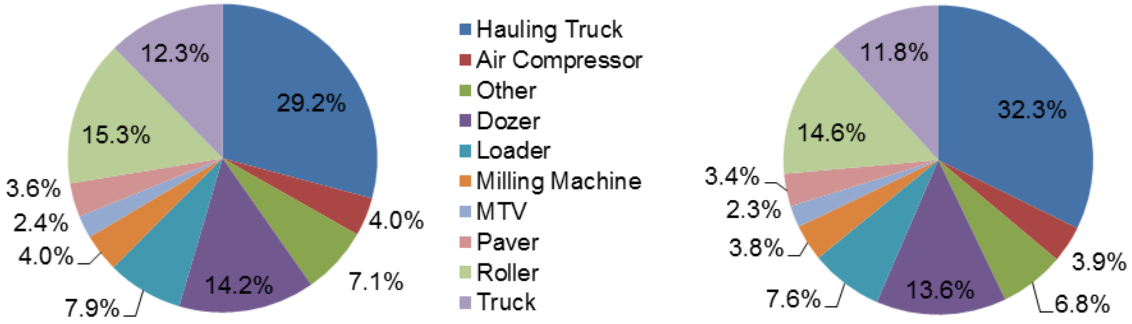
Figure 5.15 All TRACI impact results for each phase by percentage.

A breakdown of the total energy and GWP for major materials and equipment are given in Figure 5.16. The contributions from total materials are similar to that from the material production phase (Figure 5.4) with the HMA plant operations having the greatest impact, followed by binder and then aggregate. The largest contributors of equipment fuel are hauling trucks, rollers, dozers, and other trucks (i.e. distributor and water). A component-level analysis of the burdens of the materials and equipment contributions to the project's life cycle can allow analysts to observe which items should be prioritized for improvement.



(1a) Energy

(2a) GWP



(1b) Energy

(2b) GWP

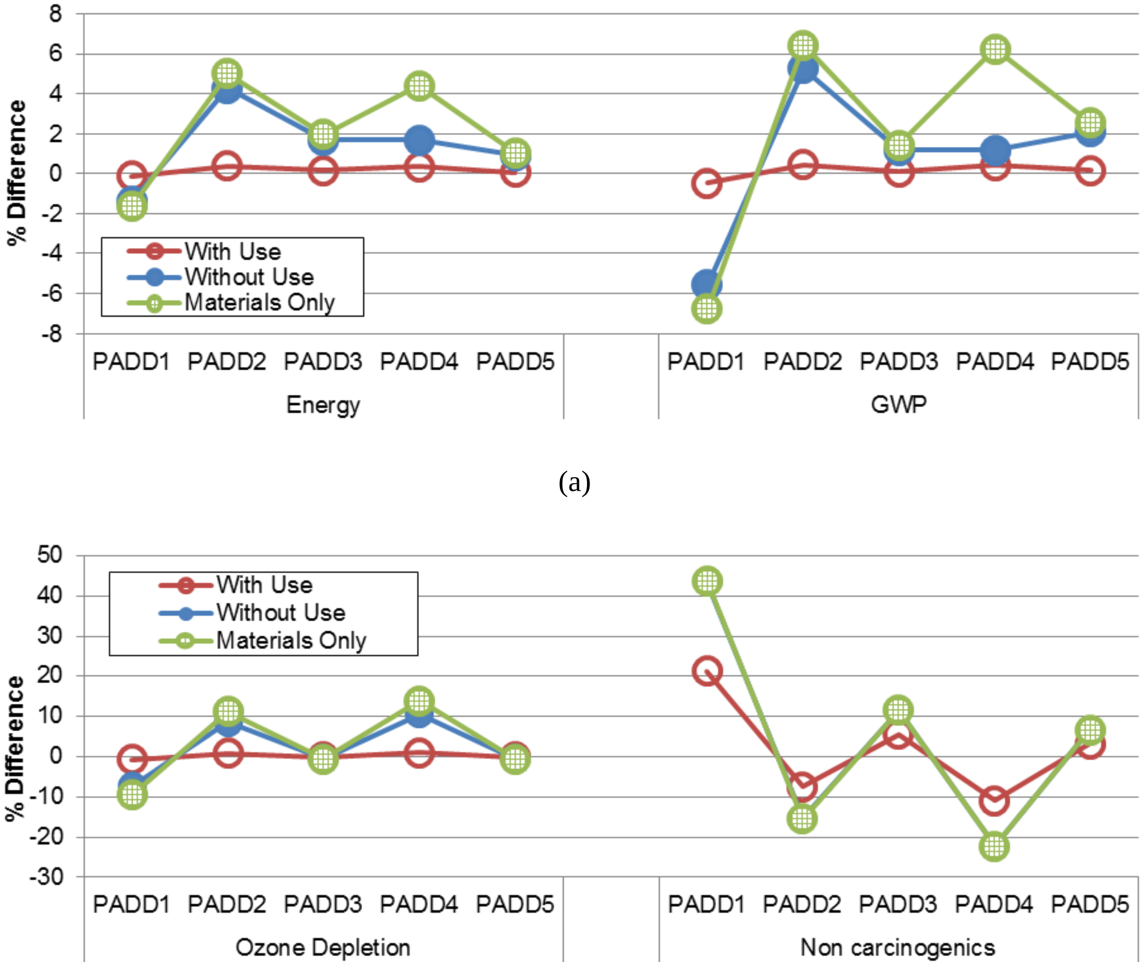
Figure 5.16 Largest (1) energy and (2) GWP contributors of (a) material production and (b) construction tasks in the life cycle.

5.8 Alternative Scenarios

Two different sets of alternative scenarios were also considered as an extension to the case study. The first scenario reevaluates the project for different PADD regions in terms of asphalt binder production. The second scenario considers different landfilling scenarios for the EOL phase. The sensitivity of the LCA results to these scenarios are given and analyzed briefly.

5.8.1 Different PADDs for Asphalt Binder

As noted in Chapter 4, the regional context of asphalt binder production can cause a difference of up to 24% in energy consumption and 41% in GWP depending on the PADD region[19]. To observe how significant these percent differences are in view of the entire life cycle, the project LCA was performed for each PADD region as well as for a national U.S. average. A summary of the percent differences for energy consumption, GWP, ozone depletion, and carcinogenics for each PADD as compared to the U.S. average is in Figure 5.17 (numerical results are in Appendix A). The results are given considering the entire pavement life cycle, the life cycle excluding the use phase, and only the material production phase.



(a)

(b)

Figure 5.17 Percent difference from U.S. average in (a) energy and GWP and (b) ozone depletion and non-carcinogenics for each PADD.

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[19] Highest differences were seen between PADD1 and PADD4.

The difference in energy and GWP reaches no further than ±0.5%, considering the entire life cycle. While this difference may seem small, it represents 807 tn.sh of CO_2E (0.46%) and 9 TJ (0.38%). The fluctuation in ozone depletion is about 20 times larger, and the percentage variation in non-carcinogenic is as high as 43% due to its abundance in binder production. However, it should be noted that the results for energy and GWP are often more reliable than other impacts, whose sensitivities may be masked and are not examined in the scope of this thesis. Rather, the contradicting resulting trends give indication that the calculation of environmental impacts are highly complex and warrant further investigation.

The level of uncertainty is much greater in the use phase models and data due to uncertainties about the predicted usage and performance of the pavement. The scenario-based analysis with and without the use phase is only performed to illustrate the relative significance of each life cycle phase. As the use phase models are improved and other use phase scenarios are considered, the percentages provided in this and the following example are subject to change.

5.8.2 Landfilling EOL for Pavement

A similar sensitivity analysis was performed for different EOL scenarios. The original case study assumed that 0% landfilling would occur and that all bound pavement materials would be removed and hauling to a plant for recycling. In this section, a 25% and 50% landfilling option is considered with the case study. The results in Figure 5.18 show the percent increases in logarithmic scale if the alternative landfilling options are considered (numerical results can be found in Appendix B).

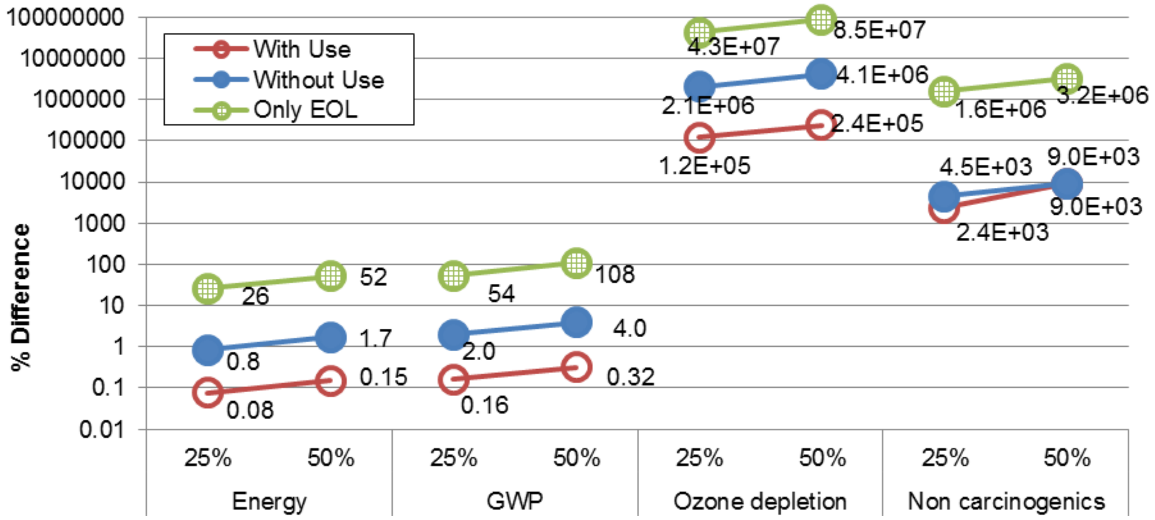

Figure 5.18 Percent difference from 0% landfilling in energy, GWP, ozone depletion, and non-carcinogenics for 25% and 50% landfilling.

The percent increases for energy and GWP are significantly higher for the EOL phase, but due to the smaller impact the EOL phase on the entire life cycle, the overall changes are less than 0.4%. The increases in ozone depletion and non-carcinogenics are exceedingly higher than the original case. It can be argued that the landfilling process overestimates the environmental impact of material disposal in the context of the functional unit. The temporal limit of the functional unit is defined to be 60 years, and the short emissions from landfilling extend 100 years past waste deposition. Temporal discounting can be considered to lessen the impact of future emissions within the present context. In general, however, the environmental impacts of landfilling must be better understood to decide how they can be appropriately considered in an LCA for pavements.

6 Summary, Conclusion, and Recommendations

In this study, the methodology, implementation, and application of life cycle assessment for pavement was investigated. A framework for a process-based LCA approach for pavement was described, incorporating all five phases of the system's life cycle. In addition to a conceptual framework, a software framework for a pavement LCA tool was also discussed. A regional life cycle inventory model for asphalt binder production was developed and presented in detail. The model provides distinct inventories for five U.S. regions. Using the framework, tool, and inventory model, a case study was evaluated for an asphalt pavement project. The entire life cycle was assessed and a sensitivity analysis was performed to gauge the importance of using regionalized asphalt binder data. The major findings, conclusions, and recommendations resulting from this thesis are presented in the remainder of this chapter.

6.1 Findings

Major findings concerning the conceptual and software LCA framework are listed below:

- A LCA framework is described for all five phases of the pavement life cycle, which includes the material production, construction, maintenance, use, and end-of-life phases. The scope of the study is specific to the Illinois region, and thus all assumptions and data used are as relevant as possible to this area.
- A life cycle inventory was compiled for 21 materials and processes as well as for 23 construction tasks. Data were taken from a combination of local data, literature sources, and commercial LCI databases, and the LCI for each process was modeled in SimaPro 7.3.3. The LCI is intended to be relevant to the Illinois region, but depending on the data available, each process embodied different levels of regionalization.
- The use phase included three major components, which are rolling resistance, carbonation, and albedo. Lighting is not in the scope of the LCA, and leachate is assumed to be negligible.
- A modular software framework is developed using Excel® spreadsheets to incorporate flexibility and user-friendliness.

In terms of the asphalt binder inventory model, the major findings are as follows:

- A LCI model for asphalt binder production was developed, whose system boundaries include crude oil extraction (and flaring), crude oil transportation, refining, refined transportation, and blending and storage. Data were collected from public databases, literature sources, and commercial LCI databases.
- The model is able to provide regionalized LCI data for each of the five U.S. PADDs. This differentiation is based on the variation in crude sources and refining fuels used in each region. The

largest differences between regions regarding energy consumption and GWP are 24% and 41%, respectively, with the East Coast having the highest environmental impacts and the Rocky Mountains having the lowest. The impact data from using the model are comparable to published values, which include a wide range of values.

- A sensitivity analysis showed that if the extra energy needed to extract Canadian oil sands is considered, the GWP for the entire production cycle could increase by up to 50%.
- Another sensitivity analysis regarding different types of allocations in the refinery found that, instead of using an economic allocation factor of 0.42, a mass allocation could increase energy consumption by up to 76%, a volume allocation by up to 46%, and an energy allocation by up to 63%.

As a result of the case study performed for the life cycle of an asphalt pavement project, the following findings are reported:

- The results of the case study showed that the use phase contributed the highest energy and GWP (91.5%, 92.3%, respectively), followed by the material production phase (3.9%, 3.4%), the maintenance phase (3.2%, 2.9%), the construction phase (1.2%, 1.2%), and finally the EOL phase (0.3%, 0.3%). Inclusion of binder feedstock increased the energy contribution of the material production phase to 9.1%.
- The highest overall contributing materials and processes were HMA plant operations, then GTR modified binder production, followed by aggregate production. The construction equipment with the highest overall contribution were hauling trucks and then rollers, dozers, and other trucks.
- The use phase was assessed using actual traffic information and a predicted roughness progression based on IRI. Throughout the 60 year life cycle of the pavement, it was calculated that nearly 14 million extra gals of fuel would be consumed due to increased road roughness as compared to a reference case with a constant IRI of 64 in/mile.
- An evaluation of all TRACI environmental impacts showed that the use phase was not the obvious highest contributor for every impact. For the categories of carcinogenics, non-carcinogenics, and ecotoxicity, the impacts in the material production and maintenance phases were comparable (and even higher for carcinogenics) to those in use phase.
- A sensitivity analysis using asphalt binder LCI data for different PADDs showed up to a 7% difference in energy and a 12% difference in GWP for the materials phase.
- Another sensitivity analysis regarding the EOL phase found a wide range of TRACI 2.2 impacts when considering 0%, 25%, and 50% landfilling. The impacts from the EOL phase with 25% and 50% landfilling scenarios had impacts that shadowed the 0% case and the use phase by multiple orders of magnitudes. This is most likely due to the longer term (<100 years) emissions that occur

during landfilling, but further investigation must be done to decide how to appropriately include landfilling as an EOL alternative.

6.2 Conclusions

The major conclusions from this thesis are summarized below:

- A LCA framework and Excel®-based tool for pavements was developed for all five phases of the system's life cycle including material production, construction, maintenance, use, and end-of-life. A regional LCI database for the Illinois region was compiled for the framework and a preliminary version of the use phase was implemented.
- An asphalt binder model was created, allowing for the consideration of differences in production processes for five regions in the U.S. This model satisfies a research gap in current LCA literature where there are no binder models for the U.S. that can account for such regional differences.
- The LCA tool was validated in a case study that evaluated the environmental impacts of a 2008–2009 Illinois Tollway full-depth asphalt reconstruction project over the entire life cycle of the pavement.

6.3 Recommendations for Future Work

There are a number of recommendations for future work that can be suggested as a result of this thesis. Simplistic assumptions and models were used at various points in this thesis to stay within the scope of the study. In addition, some of the findings and procedures can be expanded to consider scenarios beyond the scope of this study.

- The successful regionalized modeling of asphalt binder production can be expanded to other major materials and processes in the pavement life cycle. For example, a detailed model for Portland cement used in PCC can be developed, which considers variations in cementitious compositions and in plant operations. Models can also be developed to consider the effects of various parameters (e.g. type, size, mix produced, temperature, moisture, and fuel) on plant processes used in mixing PCC and asphalt concrete.
- Regarding the LCI modeling of asphalt binder, the effect of oil sands must be further studied. A sensitivity analysis demonstrated that the extra energy needed to extract oil sands will have a large impact, but this impact needs to be better quantified. Heavy oils may also require additional upgrading and refining, which was not considered in detail in this study.
- As asphalt binder is a petroleum-derived fuel, the procedures used to model binder production can also be used to model other petroleum-derived fuels, especially transportation fuels. As the impact of the construction and use phases is largely due to the consumption of gasoline and diesel, a

regionalized model for these fuels may have a significant impact on the environmental impact of these phases.

- The use phase implemented in this study is considered a preliminary approach. In terms of rolling resistance, only IRI was considered and not road texture, pavement structure or vehicle dynamics. The change in IRI was also assumed to be uniform for all ADT, which can be improved with the consideration of lane distribution factors. In addition, the traffic scenario was assumed to be fairly simplistic without any regard to future transportation scenarios that will undoubtedly contain more environmentally-friendly vehicles.
- The data pertinent to each life cycle phase has various degrees of uncertainty. The level of uncertainty is greatest in the use phase scenarios due to ambiguities regarding the future usage and performance of the pavement. Data quality indicators for each inventory data should be determined with statistical descriptors. The outcome of LCA should also be interpreted using statistical methods.
- Finally, most current pavement LCA literature and case studies focus on energy consumption and greenhouse gases. However, as seen in the case study, there are other impact categories that may not follow the same trend as the two most commonly used environmental metrics. More consideration should be given to the calculation of other impacts.

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Appendix A: Asphalt Binder Life Cycle

This appendix provides a more complete record of the calculation of foreign and domestic crude oil transportation distances initially described in Section 4.2.4.

Table A.1 Assumptions for Foreign Overseas Transportation by Oil Tanker

Exporting Country	Foreign Terminal Ports	Domestic Entry Port	Average distance (mi)
Saudi Arabia	Ras Tanura, Yanbu	Philadelphia via Suez Canal	8165
Nigeria	Bonny, Forcados, Qua Iboe, Escravos, Pennington, Brass	New Orleans	6780
Algeria	Arzew, Skikda, El-Jazair (Algiers)	Philadelphia via Suez Canal	4359
Angola	Luanda, Palanca, Malongo	New Orleans	7410
Venezuela	Puerto la Cruz, El Palito, Amuay	New Orleans	2056
Ecuador	Balao	New Orleans via Panama Canal	2222
Iraq	Basrah	Philadelphia via Suez Canal	9776

Table A.2 Assumptions for Domestic Pipeline Transportation for Foreign Crudes from Entry Ports

Exporting Country	Distance to Receiving PADD (mi)				
	PADD1	PADD2	PADD3	PADD4	PADD5
Algeria	--	800	--	--	--
Angola	--	600	100	--	2300
Argentina	--	--	100	--	--
Canada	1300	1200	--	900	1200
Ecuador	--	--	--	--	2300
Mexico	--	--	--	--	1100
Iraq	--	--	1700	--	2500
Nigeria	1300	600	100	--	--
Saudi Arabia	100	800	1700	--	2500
Venezuela	1300	--		--	--

Table A.3 Assumptions for Major Crude Transfer Hubs for each PADDs

Region	Transfer Hub (importing and exporting)
PADD1	Pittsburg, PA
PADD2	Patoka, IL
PADD3 onshore	Houston, TX
PADD3 offshore	New Orleans (70 miles offshore)
PADD4	Casper, WY
PADD5 onshore	Reno, NV (arbitrary)
PADD5 offshore	Santa Barbara, CA (2 miles offshore)

Table A.4 Assumptions for Domestic Pipeline Transportation Between PADDs

Exporter Region	**Distance to Receiving PADD (mi)**				
	To PADD1	**To PADD2**	**To PADD3**	**To PADD4**	**To PADD5**
PADD1	150	550	1330	--	--
PADD2	550	150	850	1010	--
PADD3 onshore	1330	850	150	1300	1900
PADD3 offshore	1170	760	420	1670	2270
PADD4	--	1100	1300	150	900
PADD5 onshore	--	--	--	--	150
PADD5 offshore	--	--	--	--	500

Table A.5 Assumptions for Domestic Tanker Transportation Between PADDs

Exporter Region	**Distance to Receiving PADD (mi)**				
	To PADD1	**To PADD2**	**To PADD3**	**To PADD4**	**To PADD5**
PADD1	--	--	1871	--	--
PADD2	1532	--	1410	--	--
PADD3 onshore	1871	--	--	--	4999
PADD3 offshore	1871	--	--	--	4999
PADD4	--	--	--	--	--
PADD5 onshore	--	--	--	--	--
PADD5 offshore	--	--	--	--	--

Table A.6 Energy Content Values for Fuels used in Refineries (U.S. EIA, 2013)

Fuel	**Btu/Unit**	**Unit**
Crude Oil	5800000	bbl
LPG's	3945900	bbl
Distillate	5825000	bbl
Residual Fuel Oil	6287000	bbl
Still Gas	6000000	bbl
Petroleum Coke	6024000	bbl
Other Products	5796000	bbl
Natural Gas	1023	cf
Coal	19858000	tn.sh
Purchased Electricity	3412	kWh
Purchased Steam	970	lbs

Table A.7 Energy Content and Density Values for Refined Petroleum Products (U.S. EIA, 2013)

Petroleum Product	Energy Content Btu/bbl	Densities g/gal
Liquefied Petroleum Gases		2052.5
Ethane-Ethylene	3082000	
Propane and Propylene	3836000	
Normal Butane-Butylene	4326600	
Isobutane-Isobutylene	3974000	
Finished Motor Gasoline		2791.3
Reformulated Motor Gasoline	5150000	
Conventional Motor Gasoline	5253000	
Aviation Gasoline	5048000	2675.2
Kerosene-Type Jet Fuel	5670000	3002.5
Kerosene	5670000	3080.1
Distillate Fuel Oil	5825000	3191.6
Residual Fuel Oil	6287000	3575.0
Petrochemical Feedstocks		2961.4
Naphtha for Petrochemical Feedstock Use	5248000	
Other Oils for Petrochemical Feedstock Use	5825000	
Special Naphthas	5248000	2896.5
Lubricants	6065000	3401.4
Waxes	5537000	3025.4
Petroleum Coke	6024000	4321.1
Asphalt and Road Oil	6636000	3929.0
Still Gas	6000000	32.8[20]
Miscellaneous Petroleum Products	5796000	2961.4

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[20] The density value for still gas is from GREET.

Table A.8 Average Market Values ($/mmBtu) for Petroleum Products in each PADD

Petroleum Product ($/mmBTU)	PADD1	PADD2	PADD3	PADD4	PADD5	US
Liquefied Petroleum Gases	25.37	21.10	16.86	22.58	25.75	18.95
Finished Motor Gasoline	21.86	21.78	21.45	22.18	23.28	22.03
Aviation Gasoline	24.14	24.14	24.14	24.14	24.14	24.14
Kerosene-Type Jet Fuel[21]	16.78	16.88	16.64	17.27	16.87	16.82
Kerosene	21.43	22.00	17.54	22.82	24.12	21.49
Distillate Fuel Oil	20.61	20.77	20.55	21.15	21.48	20.79
Residual Fuel Oil	10.36	9.51	8.64	6.33	12.23	10.41
Petrochemical Feedstocks	0.00	0.00	10.91	0.00	0.00	14.12
Special Naphthas	17.14	18.97	18.84	6.45	17.09	19.09
Lubricants	52.26	52.26	52.26	52.26	52.26	52.26
Waxes	23.68	23.71	23.71	23.71	23.55	23.71
Petroleum Coke	1.49	1.79	2.00	1.16	2.08	2.43
Asphalt and Road Oil	8.27	8.21	6.19	5.71	6.59	7.54
Still Gas	0.00	0.00	0.00	0.00	0.00	0.00
Miscellaneous Petroleum Products	17.03	17.32	17.43	11.95	17.39	17.43

Table A.9 Life Cycle Impacts for the Production of Asphalt for each PADD

TRACI Impact	Unit	PADD1	PADD2	PADD3	PADD4	PADD5	US
Ozone depletion	kg CFCE-11 eq	5.62E-4	6.87E-5	2.96E-4	1.62E-5	2.61E-4	2.07E-4
Global warming	kg CO_2 eq	4.62E2	2.94E2	3.43E2	2.73E2	3.26E2	3.63E2
Smog	kg O_3 eq	2.75E1	1.28E1	1.91E1	1.04E1	1.88E1	1.84E1
Acidification	kg SO_2 eq	2.76E0	2.24 E0	3.06 E0	2.04 E0	3.14 E0	2.97 E0
Eutrophication	kg N eq	4.01E-1	2.46E-1	3.34E-1	2.26E-1	3.34E-1	3.30E-1
Carcinogenics	CTUh	1.59E-5	3.98E-5	2.89E-5	4.23E-5	3.08E-5	3.34E-5
Non-carcinogenics	CTUh	1.74E-4	4.11E-4	3.02E-4	4.36E-4	3.21E-4	3.48E-4
Respiratory effects	kg $PM_{2.5}$ eq	2.00E-1	1.47E-1	2.10E-1	1.31E-1	2.18E-1	2.01E-1
Ecotoxicity	CTUe	3.23E3	7.90E3	5.78E3	8.40E3	6.17E3	6.66E3
Fossil fuel depletion	MJ surplus	6.32E3	6.14E3	6.23E3	6.14E3	6.25E3	6.27E3
Total Energy	MJ	5.81E3	4.63E3	4.99E3	4.43E3	5.19E3	5.44E3
Energy with feedstock	MJ	4.23E4	4.11E4	4.15E4	4.09E4	4.17E4	4.19E4

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[21] Assumed to be Jet Fuel in EIA SEDS.

Appendix B: Case Study Results

Detailed tables of the results from the case study are included in this section.

Table B.1 Abbreviations and Units of TRACI Impact Categories and Metrics

Name	Abbrevation	Unit
Hauling to site	Haul	tn.sh-mile
Fuel	Fuel	gals
Single score	SS	Pt
Total Energy	ENG	GJ
GWP	GWP	tn.sh CO_2 eq
Energy with Feedstock	ENG (FS)	GJ
Ozone depletion	OZ DEP	kg CFC-11 eq
Smog	SMOG	kg O_3 eq
Acidification	ACID	kg SO_2 eq
Eutrophication	EUTR	kg N eq
Carcinogenics	CARC	CTUh
Non-carcinogenics	N CARC	CTUh
Respiratory effects	RESP	kg $PM_{2.5}$ eq
Ecotoxicity	ECOTX	CTUe
Fossil fuel depletion	FF DEP	MJ surplus

Table B.2 Results for the Material Production Phase by Mix Design – Mainline

Layer	Mix	Haul to Plant	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
SMA Surface	A	1.17E5	4225	282	10651	3.31E-2	1.89E4	1.85E3	1.32E2	7.50E-3	8.16E-2	1.79E2	1.54E6	1.33E6
	B	6.65E4	4627	310	11750	3.69E-2	2.07E4	2.00E3	1.46E2	8.30E-3	9.03E-2	1.88E2	1.71E6	1.46E6
	C	1.05E5	3781	251	9797	2.96E-2	1.66E4	1.66E3	1.17E2	7.01E-3	7.60E-2	1.60E2	1.44E6	1.24E6
SMA Binder	A	3.35E5	9245	560	29191	6.02E-2	2.73E4	4.35E3	2.43E2	2.30E-2	2.46E-1	4.46E2	4.68E6	4.07E6
	B	8.43E4	4591	281	14551	3.12E-2	1.42E4	2.13E3	1.25E2	1.15E-2	1.23E-1	2.15E2	2.33E6	2.02E6
HMA Binder	A	6.80E4	3029	183	8259	1.70E-2	8.58E3	1.45E3	6.97E1	6.16E-3	6.61E-2	1.47E2	1.26E6	1.14E6
	B	2.62E5	6166	374	16247	3.42E-2	1.76E4	2.95E3	1.40E2	1.19E-2	1.28E-1	2.91E2	2.45E6	2.23E6
	C	3.99E5	10279	623	30046	6.28E-2	3.09E4	4.89E3	2.57E2	2.30E-2	2.46E-1	5.14E2	4.70E6	4.16E6
	D	9.58E4	4602	278	13604	2.80E-2	1.36E4	2.20E3	1.14E2	1.05E-2	1.12E-1	2.31E2	2.14E6	1.89E6
HMA Subbase	A	3.43E5	7602	460	18692	3.92E-2	2.08E4	3.65E3	1.61E2	1.33E-2	1.43E-1	3.46E2	2.75E6	2.55E6
	B	1.02E5	4248	256	10651	2.19E-2	1.12E4	2.03E3	8.93E1	7.66E-3	8.24E-2	1.86E2	1.58E6	1.46E6

Table B.3 Results for the Material Production Phase by Mix Design – Shoulders

Layer	Mix	Haul to Plant	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
Inner	SC	3.08E5	8156	496	24310	5.12E-2	2.45E4	3.85E3	2.08E2	1.88E-2	2.01E-1	3.92E2	3.82E6	3.37E6
	BC	1.56E5	3753	227	10248	2.13E-2	1.06E4	1.79E3	8.69E1	7.65E-3	8.20E-2	1.75E2	1.57E6	1.41E6
Outer	SC	2.95E5	7802	474	23253	4.90E-2	2.34E4	3.68E3	1.99E2	1.79E-2	1.92E-1	3.75E2	3.66E6	3.22E6
	BC	1.50E5	3590	217	9803	2.04E-2	1.01E4	1.71E3	8.31E1	7.32E-3	7.84E-2	1.67E2	1.50E6	1.35E6

Table B.4 Results for the Material Production Phase by Mix Design – Base/Subbase

Layer	Haul to Plant	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
Agg CAP	0, direct to site	3037	227	3037	3.33E-2	6.85E4	2.70E3	2.40E2	3.17E-4	5.04E-3	1.18E3	5.54E4	1.84E5
PGE	0, direct to site	5536	413	5536	6.08E-2	1.25E5	4.92E3	4.37E2	5.78E-4	9.19E-3	2.14E3	1.01E5	3.36E5

Table B.5 Results for the Construction Phase by Job

Description	Fuel	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
Hauling, plant-to-site	97156	5.0E3	420	5.0E3	6.1E-2	4.4E4	1.7E3	2.3E2	2.7E-4	9.3E-3	1.2E2	1.3E5	7.2E5
Excavation	8653	1.7E4	1200	1.7E4	2.0E-1	2.0E5	7.2E3	8.8E2	3.2E-4	1.4E-2	8.0E2	1.2E5	2.4E6
PGE	15500	1.5E3	100	1.5E3	1.8E-2	1.8E4	6.3E2	7.8E1	2.9E-5	1.2E-3	6.8E1	1.0E4	2.1E5
Aggregate Cap	6959	2.6E3	180	2.6E3	3.2E-2	3.2E4	1.1E3	1.4E2	5.2E-5	2.2E-3	1.3E2	1.9E4	3.8E5
FDHMA	8099	1.2E3	83	1.2E3	1.4E-2	1.4E4	5.1E2	6.2E1	2.3E-5	1.0E-3	5.7E1	8.4E3	1.7E5
HMA Shoulders	97156	1.4E3	97	1.4E3	1.7E-2	1.6E4	5.9E2	7.2E1	2.7E-5	1.2E-3	6.5E1	9.8E3	2.0E5

Table B.6 Results for the Maintenance Production Phase by Year – Mainline Activities

Yr	Description	Fuel	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
3	Rout & Seal (100%)	937	160	11	160	1.95E-3	2.00E3	7.13E1	8.56	3.12E-6	1.34E-4	8.74	1.13E3	2.28E4
	Sealant Production		46	3	296	5.04E-4	1.15E2	2.13E1	1.81	2.78E-4	2.88E-3	1.36	5.54E4	4.39E4
8	Rout & Seal (150%)	703	120	8	120	1.46E-3	1.50E3	5.34E1	6.42	2.34E-6	1.01E-4	6.55	8.48E2	1.71E4
	Sealant Production		35	2	222	3.78E-4	8.66E1	1.60E1	1.36	2.08E-4	2.16E-3	1.02	4.16E4	3.29E4
	Patching (%)	152	32	2	32	3.86E-4	3.75E2	1.35E1	1.66	8.16E-7	3.24E-5	1.79	3.37E2	4.52E3
	Mix Production		231	15	587	1.84E-3	1.04E3	1.00E2	7.27	4.15E-4	4.51E-3	9.39	8.53E4	7.31E4
15	Milling (2-in)	529	90	6	90	1.10E-3	1.32E3	4.57E1	5.18	1.76E-6	7.59E-5	4.82	6.39E2	1.29E4
	Patching (1.0%)	506	106	8	106	1.29E-3	1.25E3	4.49E1	5.52	2.72E-6	1.08E-4	5.97	1.12E3	1.51E4
	Mix Production		771	52	1957	6.14E-3	3.45E3	3.34E2	24.2	1.38E-3	1.50E-2	31.3	2.84E5	2.44E5
	HMA Overlay (2-in)	3083	848	64	848	1.03E-2	9.06E3	3.33E2	42.6	2.75E-5	1.03E-3	32.1	1.23E4	1.21E5
	Mix Production		12842	860	32614	1.02E-1	5.75E4	5.56E3	404	2.30E-2	2.51E-1	522	4.74E6	4.06E6
23	Rout & Seal (150%)	703	120	8	120	1.46E-3	1.50E3	5.34E1	6.42	2.34E-6	1.01E-4	6.55	8.48E2	1.71E4
	Sealant Production		35	2	222	3.78E-4	8.66E1	1.60E1	1.36	2.08E-4	2.16E-3	1.02	4.16E4	3.29E4
	Patching (0.3%)	152	32	2	32	3.86E-4	3.75E2	1.35E1	1.66	8.16E-7	3.24E-5	1.79	3.37E2	4.52E3
	Mix Production		231	15	587	1.84E-3	1.04E3	1.00E2	7.27	4.15E-4	4.51E-3	9.39	8.53E4	7.31E4
30	Milling (4-in)	1059	181	13	181	2.20E-3	2.65E3	9.14E1	10.4	3.53E-6	1.52E-4	9.65	1.28E3	2.58E4
	Patching (1.0%)	506	106	8	106	1.29E-3	1.25E3	4.49E1	5.52	2.72E-6	1.08E-4	5.97	1.12E3	1.51E4

	Mix Production		771	52	1957	6.14E-3	3.45E3	3.34E2	24.2	1.38E-3	1.50E-2	31.3	2.84E5	2.44E5
	HMA Overlay (4-in)	6165	1696	128	1696	2.06E-2	1.81E4	6.65E2	85.1	5.51E-5	2.07E-3	64.2	2.46E4	2.42E5
	Mix Production		25684	1719	65227	2.05E-1	1.15E5	1.11E4	808	4.61E-2	5.01E-1	1040	9.48E6	8.12E6
38	Rout & Seal (150%)	703	120	8	120	1.46E-3	1.50E3	5.34E1	6.42	2.34E-6	1.01E-4	6.55	8.48E2	1.71E4
	Sealant Production		35	2	222	3.78E-4	8.66E1	1.60E1	1.36	2.08E-4	2.16E-3	1.02	4.16E4	3.29E4
	Patching (0.3%)	152	32	2	32	3.86E-4	3.75E2	1.35E1	1.66	8.16E-7	3.24E-5	1.79	3.37E2	4.52E3
	Mix Production		231	15	587	1.84E-3	1.04E3	1.00E2	7.27	4.15E-4	4.51E-3	9.39	8.53E4	7.31E4
45	Milling (2-in)	529	90	6	90	1.10E-3	1.32E3	4.57E1	5.18	1.76E-6	7.59E-5	4.82	6.39E2	1.29E4
	Patching (1.0%)	506	106	8	106	1.29E-3	1.25E3	4.49E1	5.52	2.72E-6	1.08E-4	5.97	1.12E3	1.51E4
	Mix Production		771	52	1957	6.14E-3	3.45E3	3.34E2	24.2	1.38E-3	1.50E-2	31.3	2.84E5	2.44E5
	HMA Overlay (2-in)	3083	848	64	848	1.03E-2	9.06E3	3.33E2	42.6	2.75E-5	1.03E-3	32.1	1.23E4	1.21E5
	Mix Production		12842	860	32614	1.02E-1	5.75E4	5.56E3	404	2.30E-2	2.51E-1	522	4.74E6	4.06E6
53	Rout & Seal (150%)	703	120	8	120	1.46E-3	1.50E3	5.34E1	6.42	2.34E-6	1.01E-4	6.55	8.48E2	1.71E4
	Sealant Production		35	2	222	3.78E-4	8.66E1	1.60E1	1.36	2.08E-4	2.16E-3	1.02	4.16E4	3.29E4
	Patching (0.3%)	152	32	2	32	3.86E-4	3.75E2	1.35E1	1.66	8.16E-7	3.24E-5	1.79	3.37E2	4.52E3
	Mix Production		231	15	587	1.84E-3	1.04E3	1.00E2	7.27	4.15E-4	4.51E-3	9.39	8.53E4	7.31E4

Table B.7 Results for the Maintenance Production Phase by Year – Shoulder Activities

Yr	Description	Fuel	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
8	Rout & Seal (400%)	3747	640	45	640	7.79E-3	8.01E3	2.85E2	34.2	1.25E-5	5.38E-4	35.0	4.52E3	9.13E4
	Sealant Production		185	11	1183	2.02E-3	4.62E2	8.53E1	7.24	1.11E-3	1.15E-2	5.45	2.22E5	1.76E5
	Microsurface	355	61	4	61	7.39E-4	7.84E2	2.77E1	3.29	1.18E-6	5.10E-5	3.12	4.29E2	8.65E3
	Seal Production		712	43	5255	9.32E-3	2.93E3	3.41E2	36.3	4.98E-3	5.15E-2	34.0	9.86E5	7.72E5
15	Milling (2-in)	322	55	4	55	6.69E-4	8.05E2	2.78E1	3.15	1.07E-6	4.62E-5	2.93	3.89E2	7.84E3
	Patching (2.0%)	615	129	9	129	1.56E-3	1.52E3	5.46E1	6.71	3.31E-6	1.31E-4	7.26	1.37E3	1.83E4
	Mix Production		937	63	2380	7.47E-3	4.20E3	4.06E2	29.5	1.68E-3	1.83E-2	38.1	3.46E5	2.96E5
	HMA Inlay (2-in)	1791	655	51	655	7.98E-3	6.70E3	2.48E2	32.3	2.48E-5	9.01E-4	22.4	1.15E4	9.34E4
	Mix Production		5319	323	15854	3.34E-2	1.60E4	2.51E3	135	1.22E-2	1.31E-1	256	2.49E6	2.20E6
23	Rout & Seal (400%)	3747	640	45	640	7.79E-3	8.01E3	2.85E2	34.2	1.25E-5	5.38E-4	35.0	4.52E3	9.13E4

	Sealant Production		185	11	1183	2.02E-3	4.62E2	8.53E1	7.24	1.11E-3	1.15E-2	5.45	2.22E5	1.76E5
	Microsurface	355	61	4	61	7.39E-4	7.84E2	2.77E1	3.29	1.18E-6	5.10E-5	3.12	4.29E2	8.65E3
	Seal Production		712	43	5255	9.32E-3	2.93E3	3.41E2	36.3	4.98E-3	5.15E-2	34.0	9.86E5	7.72E5
30	Milling (2-in)	322	55	4	55	6.69E-4	8.05E2	2.78E1	3.15	1.07E-6	4.62E-5	2.93	3.89E2	7.84E3
	Patching (2.0%)	615	129	9	129	1.56E-3	1.52E3	5.46E1	6.71	3.31E-6	1.31E-4	7.26	1.37E3	1.83E4
	Mix Production		937	63	2380	7.47E-3	4.20E3	4.06E2	29.5	1.68E-3	1.83E-2	38.1	3.46E5	2.96E5
	HMA Inlay (2-in)	1791	655	51	655	7.98E-3	6.70E3	2.48E2	32.3	2.48E-5	9.01E-4	22.4	1.15E4	9.34E4
	Mix Production		5319	323	15854	3.34E-2	1.60E4	2.51E3	135	1.22E-2	1.31E-1	256	2.49E6	2.20E6
38	Rout & Seal (400%)	3747	640	45	640	7.79E-3	8.01E3	2.85E2	34.2	1.25E-5	5.38E-4	35.0	4.52E3	9.13E4
	Sealant Production		185	11	1183	2.02E-3	4.62E2	8.53E1	7.24	1.11E-3	1.15E-2	5.45	2.22E5	1.76E5
	Microsurface	355	61	4	61	7.39E-4	7.84E2	2.77E1	3.29	1.18E-6	5.10E-5	3.12	4.29E2	8.65E3
	Seal Production		712	43	5255	9.32E-3	2.93E3	3.41E2	36.3	4.98E-3	5.15E-2	34.0	9.86E5	7.72E5
45	Milling (2-in)	322	55	4	55	6.69E-4	8.05E2	2.78E1	3.15	1.07E-6	4.62E-5	2.93	3.89E2	7.84E3
	Patching (2.0%)	615	129	9	129	1.56E-3	1.52E3	5.46E1	6.71	3.31E-6	1.31E-4	7.26	1.37E3	1.83E4
	Mix Production		937	63	2380	7.47E-3	4.20E3	4.06E2	29.5	1.68E-3	1.83E-2	38.1	3.46E5	2.96E5
	HMA Inlay (2-in)	1791	655	51	655	7.98E-3	6.70E3	2.48E2	32.3	2.48E-5	9.01E-4	22.4	1.15E4	9.34E4
	Mix Production		5319	323	15854	3.34E-2	1.60E4	2.51E3	135	1.22E-2	1.31E-1	256	2.49E6	2.20E6
53	Rout & Seal (400%)	3747	640	45	640	7.79E-3	8.01E3	2.85E2	34.2	1.25E-5	5.38E-4	35.0	4.52E3	9.13E4
	Sealant Production		185	11	1183	2.02E-3	4.62E2	8.53E1	7.24	1.11E-3	1.15E-2	5.45	2.22E5	1.76E5
	Microsurface	355	61	4	61	7.39E-4	7.84E2	2.77E1	3.29	1.18E-6	5.10E-5	3.12	4.29E2	8.65E3
	Seal Production		712	43	5255	9.32E-3	2.93E3	3.41E2	36.3	4.98E-3	5.15E-2	34.0	9.86E5	7.72E5

Table B.8 Summary of TRACI Impact Contributions from Each Phase

Phase	**Total Energy**		**GWP**		**Energy (w/ Feedstock)**		**Ozone depletion**	
	MJ	**%**	**kg CO_2E**	**%**	**MJ**	**%**	**kg CFC-11 eq**	**%**
Material Production	9.43E1	1.9	5.91E3	1.7	2.50E2	4.6	6.30E-1	1.0
Construction	2.83E1	0.6	2.05E3	0.6	2.83E1	0.5	3.45E-1	0.6
Maintenance	7.71E1	1.6	5.04E3	1.4	2.20E2	4.0	6.05E-1	1.0
Use	2.22E3	45.7	1.61E5	46.1	2.22E3	40.7	2.92E1	47.3
End-of-Life	7.09E0	0.1	5.24E2	0.1	7.09E0	0.1	8.63E-2	0.1
Total	2.43E3	50.0	1.75E5	50.0	2.73E3	50.0	3.09E1	50.0

Phase	**Smog**		**Acidification**		**Eutrophication**		**Carcinogenics**	
	kg O_3 eq	**%**	**kg SO_2 eq**	**%**	**kg N eq**	**%**	**CTUh**	**%**
Material Production	4.62E5	2.1	4.78E4	4.0	2.85E3	1.7	1.82E-1	20.1
Construction	3.25E5	1.4	1.18E4	1.0	1.46E3	0.9	7.24E-4	0.1
Maintenance	3.19E5	1.4	3.42E4	2.9	2.39E3	1.5	1.65E-1	18.2
Use	1.01E7	44.8	4.97E5	41.9	7.45E4	45.7	1.05E-1	11.5
End-of-Life	7.15E4	0.3	2.65E3	0.2	3.48E2	0.2	3.05E-4	0.0
Total	1.12E7	50.0	5.93E5	50.0	8.16E4	50.0	4.53E-1	50.0

Phase	**Non-Carcinogenics**		**Respiratory effects**		**Ecotoxicity**		**Fossil fuel depletion**	
	CTUh	**%**	**kg $PM_{2.5}$ eq**	**%**	**CTUe**	**%**	**MJ surplus**	**%**
Material Production	1.96E0	13.7	7.33E3	8.3	3.73E7	17.2	3.34E7	4.4
Construction	2.88E-2	0.2	1.23E3	1.4	2.99E5	0.1	4.04E6	0.5
Maintenance	1.78E0	12.4	3.26E3	3.7	3.37E7	15.5	2.87E7	3.8
Use	3.40E0	23.7	3.21E4	36.4	3.70E7	17.1	3.15E8	41.2
End-of-Life	1.07E-2	0.1	2.08E2	0.2	1.46E5	0.1	1.01E6	0.1
Total	7.18E0	50.0	4.41E4	50.0	1.08E8	50.0	3.82E8	50.0

Table B.9 Total TRACI Life Cycle Impacts for the Alternative PADD Scenarios

PADD	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
1	2447	1.766E5	2745	35.01	1.143E7	6.004E5	8.320E4	0.2578	5.244	4.491E4	7.023E7	3.843E8
2[22]	2434	1.751E5	2733	31.00	1.131E7	5.945E5	8.193E4	0.4515	7.168	4.439E4	1.081E8	3.825E8
3	2440	1.757E5	2739	32.83	1.136E7	6.028E5	8.265E4	0.3637	6.290	4.499E4	9.110E7	3.836E8
4	2435	1.751E5	2734	30.54	1.129E7	5.945E5	8.176E4	0.4738	7.390	4.435E4	1.126E8	3.828E8
5	2442	1.755E5	2740	32.55	1.136E7	6.035E5	8.265E4	0.3797	6.450	4.506E4	9.429E7	3.837E8
U.S.	2444	1.758E5	2742	32.10	1.136E7	6.021E5	8.262E4	0.4008	6.666	4.492E4	9.832E7	3.839E8

Table B.10 Total TRACI Life Cycle Impacts for the Alternative Landfilling Scenarios

Landfilling	ENG	GWP	ENG (FS)	OZ DEP	SMOG	ACID	EUTR	CARC	N CARC	RESP	ECOTX	FF DEP
0%[23]	2441	1.756E5	2740	31.02	1.135E7	5.975E5	8.212E4	0.4535	7.193	4.457E4	1.086E8	3.835E8
25%	2443	1.759E5	2740	36890	1.134E7	5.976E5	8.210E4	0.4568	178.3	9.682E4	1.089E8	3.834E8
50%	2445	1.761E5	2739	73750	1.134E7	5.976E5	8.207E4	0.4600	349.5	1.491E5	1.091E8	3.834E8

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[22] Original case study
[23] Original case study