DEVELOPMENT AND IMPLEMENTATION OF COMPREHENSIVE REGIONALIZED PAVEMENT LIFE-CYCLE ASSESSMENT

BY

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DISSERTATION

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ABSTRACT

The use of life-cycle assessment (LCA) to evaluate the environmental impacts of pavement systems is a topic that stakeholders in academia, industry, and government have actively engaged with in the last two decades. The LCA methodology aims to provide quantitative environmental metrics such as energy consumption and greenhouse gases regarding the cradle-to-grave impacts accumulated over the pavement's life-cycle. While research progress has been made to improve the inventory data and models used in pavement LCA, the connectivity between development of the LCA, application of an LCA software, and interpretation of LCA results have not yet been thoroughly addressed. Thus, in order to further the practical utilization of pavement LCA, work must be done to evaluate how LCA consumers and decision makers can apply and interpret LCA results and how methodological issues may affect LCA results.

The first portion of this dissertation concerns the compilation and application of regional life-cycle inventory data for initial pavement construction. Using data modeled to represent the Northern Illinois region, various pavement mixtures and pay item activities are evaluated for initial environmental impacts due to material production and construction processes. To address the limitations in possessing only partial LCA impacts, a scenario-based analysis is used to consider the effect of future pavement performance on life-cycle environmental impacts. In addition, economic impacts are also calculated for mixes and pay items, and a cost-effectiveness analysis is conducted to expand the pay item environmental assessment into a useful set of metrics for agencies.

Building upon the inventory data compiled, a full LCA framework and software is then implemented. The roadway/roadside software is designed to consider each life-cycle stage (i.e., materials and construction, maintenance and rehabilitation, use, and end-of-life) of major roadway/roadside elements including drainage, landscape, lighting, pavement, and structures using pay items to facilitate agency utilization. A set of fourteen diverse pavement construction contracts are analyzed using the LCA software and their results are visualized and interpreted as relevant to transportation agencies.

The final portion of this dissertation evaluates key interpretation issues related to pavement LCA. A series of sensitivity analyses are performed on major methodological choices to determine which decisions and parameters ultimately have a significant effect on the overall LCA results. Furthermore, two methods for incorporating uncertainty into the LCA are also implemented - one using a simplistic probabilistic approach and the other using an informed Bayesian updating approach. The effects of considering data uncertainty in LCA, especially for comparative analyses, are addressed.

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LIST OF ACRONYMS

Acronym	Description
AADT	annual daily traffic
ABR	asphalt binder replacement
AC	asphalt concrete
AE	air entraining
asPECT	asphalt Pavement Embodied Carbon Tool
ATPB	asphalt treated permeable base
BFS	blast furnace slag
BMC	Bayesian Monte Carlo
CAIT	Climate Analysis Indicators Tool
CE	cost effectiveness
CED	cumulative energy demand
CO_2	carbon dioxide
CO	carbon monoxide
DQI	data quality indicators
DQPM	data quality pedigree matrix
EB	eastbound
ECORCE	ECO-comparator applied to Road Construction and Maintenance
EOL	end-of-life
EPA	Environmental Protection Agency
EPD	Environmental Product Declarations
FHWA	Federal Highway Administration
FRAP	fractionated recycled asphalt pavement
GASCAP	Greenhouse-Gas Assessment Spreadsheet for CAPital Project
GDP	gross domestic product
GGBFS	Ground granulated blast furnace slag
GHG	greenhouse gases
G_{mb}	bulk specific gravity
GWP	global warming potential
HC	hydrocarbons
HMA	hot-mix asphalt
HP	horsepower
IDOT	Illinois Department of Transportation
IRI	international roughness index
ISO	International Organization for Standardization
JCPC	jointed plain concrete pavement

kg CO_2e	carbon dioxide equivalence
lb/yd^3	pounds per cubic yard
LCA	life-cycle assessment
LCCA	life-cycle cost analysis
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
M&C	materials and construction
M&R	maintenance and rehabilitation
MJ	megajoule
MWSS	manufacturer waste scrap shingles
NB	northbound
NIST	National Institute of Standards and Technology
NMHC	non-methane hydrocarbons
NO_X	nitrogen oxides
OGFC	open-graded friction surface course
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCC	Portland cement concrete
PE-2	Project Emission Estimator
PEF	primary energy as fuel
PEM	primary energy as material
PM	particulate matter
RAP	recycled asphalt pavement
RAS	recycled asphalt shingles
RCA	recycled concrete aggregate
REP	respiratory effects
rrLCA 1.0	roadway/roadside LCA software version 1.0
SB	southbound
SCM	secondary cementitious material
SD	standard deviation
sGSD	squared geometric standard deviation
SMA	stone mastic asphalt
SS	single score
TOSS	tear-off scrap shingles
TPE	total primary energy
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
US-EI 2.2	US-Ecoinvent version 2.2
VBA	Visual Basic for Applications
VMT	vehicle-mile-traveled
WB	westbound
WMA	warm-mix asphalt
yd^2	square yards

CHAPTER 1

INTRODUCTION

1.1 Overview

There are over 22 million miles of paved and unpaved roadways worldwide (CIA, 2016), with the United States (U.S.) maintaining the largest road network at 4.2 million miles for its 214 million users (FHWA, 2014). In order to manage this road network and an additional 650 million square yards of paved airport runways, the U.S. spends more than $200 billion annually of combined federal, state, and local funding (FHWA 2014; Agrawal, 2009). In addition to the enormous social and economic impacts of pavement infrastructure, there is also a significant environmental impact, with the overall transportation sector consistently contributing to 27% and 28% of national global greenhouse gases (GHGs) and energy consumption, respectively (EPA, 2013). While the pavement industry has employed a variety of innovative materials and techniques to lessen its environmental impact, the effects of these strategies must be systematically evaluated.

A number of approaches are used to assess pavement systems with regards to the triple bottom line of social, economic, and environmental sustainability. These approaches can be generally categorized as either qualitative rating systems or quantitative accounting methodologies such as carbon footprinting, life-cycle cost analysis (LCCA), or environmental life-cycle assessment (LCA). Of particular interest is the use of LCA to systematically evaluate the environmental impacts of pavement systems. This application of LCA has recently become internationally recognized due to academic, industrial, and governmental interest. The use of LCA to analyze pavements was first recognized in Europe, with the earliest LCA study conducted in Finland in 1996 (Häkkinen & Mäkelä). Since then, a number of LCA software (mostly privately held) have been developed in Europe, with countries such as the Netherlands developing nationwide software (Dubocalc) to incorporate environmental considerations into their bidding process (Rijkswaterstaat, 2015). In the U.S., various individual studies and tools emerged in the 2000s before a national effort by the Federal Highway Administration (FHWA) released in a comprehensive framework document in July 2016 to provide guidance and commentary on the implementation of LCA for pavement (Harvey et al.).

While LCA as a general methodology does have governing principles from the International Organization for Standardization (ISO), specific guidelines for pavement LCA are recent efforts and

existing implementations of LCA as case studies or software have not been uniform (AzariJafari et al., 2016). Currently, numerous project-level LCA case studies have been reported, often to compare various pavement design alternatives for a specific site context (Häkkinen & Mäkelä, 1996; Stripple, 2001; Meil, 2006; Wang et al., 2012; Kang et al., 2014), while a variety of open source and commercial pavement LCA software are also available for general use (Horvath, 2003b; Athena, 2015; GASCAP, 2014). A large volume of research has focused on improving the implementation of pavement LCA in terms of compiling higher quality inventory data (Stripple, 2001; Zapata & Gambatese, 2005; Meli, 2006; Kang et al., 2014) or developing models to better estimate the environmental effects that should be attributed to pavement during its use (Akbari, 2009; Wang et al., 2012; Yu & Lu, 2012). The majority of the studies discussed are for roadways and highways, while fewer exist for airport pavement (Kulikowski et al. 2016). In addition, while earlier LCA literature predominantly addressed project-level context, work has also been done to expand the application of LCA to the network-level (Bryce et al., 2015) or to optimize maintenance schedules (Zhang et al., 2010; Reger et al., 2014) with implications on agency-wide decision-making. However, as efforts are being made to incorporate LCA into decision-making, issues surrounding the application and interpretation of LCA must also be addressed. Fewer studies exist that evaluate specifically how LCA consumers and decision makers may apply or interpret pavement LCA results or how the effects of methodological choices and data uncertainty may affect LCA results.

1.2 Problem Statement

Growing interest in LCA research and its implications on the pavement industry has led to the development of various guidelines, literature, case studies, and software in the recent two decades. However, with guidelines established only recently in 2016 in the U.S., implementations of pavement LCA have varied widely in terms of goal, context, comprehensiveness, and methodological choices, reducing the applicability of these efforts to industry and undermining consistency in the interpretation of LCA results.

In the U.S. there are not yet any pavement LCA tools or implementations that are universally accepted. Many of the challenges in developing robust LCA tools are related to the quality and appropriateness of life-cycle inventory (LCI) data, limitations in interpreting LCA results, ambiguity surrounding the consequences of methodological choices, and approaches to treating the uncertainty inherent in such a data-driven assessment technique. These limitations create major challenges for agencies attempting to systematically incorporate environmental considerations into their decision-making process using LCA. While growing progress has been seen in the technical implementation of LCA for pavement system, questions surrounding the application and interpretation of pavement LCA must also be addressed in order for LCA to be effectively used to inform decision-making.

1.3 Objectives and Methodology

The main goal of this research is to address issues related to the application and interpretation of pavement LCA results using realistic case studies. In order to meet this goal, the following objectives will be accomplished in this research.

- Compile a comprehensive and regionally appropriate LCI database for evaluating pavement systems in Northern Illinois.
- Use the LCI database to conduct cradle-to-gate environmental analyses for pavement mixtures and cradle-to-ground environmental analyses for construction activities as defined by pay (i.e. bid) items.
- Consider the effect of future pavement performance on initial cradle-to-gate environmental benefits of recycled versus virgin asphalt mixtures.
- Evaluate the relationship between initial economic and environmental impacts for construction activities and quantify the cost-benefit value of common sustainable strategies.
- Develop a complete LCA for a road system using the LCI database, including all life-cycle stages and roadway/roadside elements and implement the LCA in a software in such a way as is relevant to transportation agencies.
- Use the LCA software to analyze a series of pavement construction projects and interpret the LCA results relevant to the perspective of transportation agencies.
- Evaluate the sensitivity of important parameters and methodological choices in the LCA and make recommendations regarding their significance.
- Develop informed methods of incorporating the effects of uncertainties resulting from LCI data in the LCA.

This research employs the use of LCA, which is governed by the ISO 14040 series (2006a). Thus, guidelines regarding the four phases of LCA prescribed by ISO (i.e. goal and scope definition, inventory analysis, impact assessment, and interpretation) will be followed along with pavement-specific guidelines as given by the FHWA's pavement LCA framework (Harvey et al., 2016).

Overall, the work in this research can be divided into three major tasks. First, a partial LCA for the materials and construction life-cycle stages of the pavement system is conducted. The LCI data required are assembled for the desired region, and a collection of mixes and construction activities are systematically assessed for their environmental impacts. The applications and limitations of these assessments are evaluated when future pavement performance and economic cost are also considered using scenario-based and cost-benefit approaches, respectively. Second, a full LCA for the road system is considered for all life-

cycle stages and for various roadway/roadside elements. A LCA software is then developed in a way that can be directly implemented by and applicable to a transportation agency. Multiple pavement projects are evaluated, and conclusions and limitations in application and interpretation are demonstrated. Third, issues related to sensitivity and uncertainty in the LCA are addressed. Important parameters and methodological choices in the LCA are evaluated for sensitivity, and recommendations are made regarding their significance. Data uncertainty is also evaluated, and informed probabilistic distributions are applied to the LCI data using Bayesian updating techniques to incorporate knowledge about temporal and regional characteristics.

1.4 Research Contribution

The contribution of this dissertation regarding the application and interpretation of pavement LCA results will be of interest to researchers, practitioners, and consumers of pavement LCA. The dissertation addresses practical questions of implementation and application as well as methodological questions related to interpretation. More specifically, the following topics will be addressed in this work.

The initial environmental impacts from producing pavement mixes have been readily studied in literature. In asphalt mixes, the use of recycled material has been shown to decrease environmental impacts from production due to the reduced amount of virgin asphalt binder and aggregate required. However, many of these analyses only consider initial production impacts and do not consider the use and performance of the mixtures. In order to compare the tradeoffs between initial environmental benefits and future performance, a scenario-based analysis is used to evaluate expected life expectancy of the mixture. The approach and results from this work will be useful to decision makers interested in comparing environmental impacts for alternative asphalt mixtures (e.g. an overlay) that extend beyond initial impacts and also consider risks and tradeoffs in expected pavement life.

Various sustainable strategies have been identified in the pavement industry (e.g. warm-mix asphalt, use of recycled materials) that may decrease initial cost and/or environmental impacts. Clearly, practices that can reduce both cost and environmental impacts are most desirable for stakeholders, but the relationship between these two parameters have not been systematically studied for pavement construction. Thus, this work will assess the relationship between economic and environmental impacts of construction activities, ultimately developing a set of cost-benefit values for various common sustainable strategies. By providing a methodology to identify strategies that can provide the most desirable cost-benefit values, this work demonstrates an approach agencies can use to gain information about which strategies to prioritize.

A number of pavement LCA studies and software have emerged in recent years. However, in the U.S., no transportation agency has fully adopted the use of LCA for their infrastructure projects. There are many

barriers for agencies to use LCA, including lack of appropriate LCI data, lack of a software that can be readily adapted to current agency procedures, and lack of experience in interpreting LCA results. A LCA software is developed in this work that is specifically designed to be used by an agency through the incorporation of regional LCI data and pay items. A series of analyses are conducted using the software and the results are interpreted from an agency perspective. This work is useful to agencies as an example of how LCA can be adapted by an agency for pavement construction and provide relevant LCA results.

As a methodology, LCA can be applied to any product system, and for each system, there are general and product-specific methodological choices that must be made by the LCA practitioner. The effects of these choices and parameters on the LCA results may or may not be significant. In pavement LCA, methodological choices are not treated consistently across literature; thus, this work seeks to determine the significance of important parameters and methodological choices relevant to pavement LCA using a series of sensitivity analyses. This work will be of interest to LCA practitioners regarding the significance of major methodological choices on overall LCA results as well as to industry stakeholders and decision makers regarding which input parameters are most significant to overall LCA results.

LCA is a data-driven methodology whose results rely largely on the quality of the LCI data used. It is impossible to collect primary data for all processes involved in an LCA that precisely capture all characteristics of the product system. Currently, when uncertainty with respect to LCI data is included in pavement LCA, it is often incorporated using probabilistic distributions developed using basic qualitative observations. This work instead considers additional knowledge about the relationship between LCI data and the process it is intended to represent in order to better characterize the uncertainty underlying the LCA.

1.5 Dissertation Organization

An introduction to the dissertation along with the problem statement, objectives, and scope were given in this chapter. The next two chapters focus on quantifying and interpreting cradle-to-gate and cradle-to-ground analyses of pavement mixtures and construction activities. In Chapter 2, the initial environmental and cost savings from producing recycled versus virgin asphalt mixes are determined, and the effects of considering mixture performance and the resulting tradeoffs in life-cycle environmental impacts are evaluated using a scenario-based analysis. In Chapter 3, a database of pavement mixtures and pay items are analyzed and used to develop cost-effectiveness values for common sustainable strategies used in highway construction. Chapter 4 expands the work to consider the complete life cycle. This chapter describes a LCA software that was developed and demonstrates the use of the software in assessing the environmental impacts of various types of pavement projects for an agency.

Chapters 5 and 6 address interpretation issues related to sensitivity and uncertainty in the pavement LCA approach used in the previous chapters. A series of sensitivity analyses are conducted in Chapter 5 to determine the influence of various parameters and methodological choices on the LCA results. Two uncertainty analysis methods are evaluated in Chapter 6 to consider the effect of variations in inventory data quality on LCA results. Finally, Chapter 7 includes the findings, conclusions, and recommendations of the dissertation.

CHAPTER 2

CONSIDERING FUTURE PERFORMANCE IN THE ASSESSMENT OF ENVIRONMENTAL IMPACTS FOR ASPHALT MIXTURES[1]

2.1 Motivation

In this chapter, the initial and potential future environmental effects of using recycled materials in asphalt mixtures are examined in detail. Recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) are commonly used in asphalt mixtures as substitutes for virgin asphalt binder and coarse and/or fine aggregate. Due to the resulting reduction in virgin materials when utilizing RAP and RAS, contractors and agencies expect savings in cost as well as a reduction of impacts on the environment. By compiling environmental data regarding the production of virgin asphalt binder and aggregate compared to that for processing RAP and RAS, the corresponding environmental savings for producing recycled versus virgin asphalt concrete (AC) mixtures can be determined. A similar procedure can be used to also quantify cost savings of recycled AC mixtures.

The expected cost and environmental impact savings from using recycled AC mixtures are "initial savings" that are realized when considering only the cradle-to-gate lifespan of the pavement. With the use of RAP and/or RAS, the AC mixture composition changes and consequently the pavement's potential performance is affected. Thus, in order to obtain a more holistic understanding of the effects of using RAP and RAS on the environmental impacts of AC mixtures, life-cycle concepts must be employed to consider also the expected lifetime and use of the pavement. For example, a poor performing pavement becomes rougher over time, causing vehicles to expend more fuel, while a superior performing pavement has a slower roughness progression over time, causing vehicles to expend less fuel. As the performance of recycled mixtures is difficult to predict, a scenario-based analysis is used in this chapter to assess the potential tradeoffs in initial savings versus expected pavement life. The outcome of such an analysis is useful to

[1] The work in this chapter has been published as "Environmental and economic analyses of recycled asphalt concrete mixtures based on material production and potential performance" in *Resources, Conservation and Recycling Volume 104, 141–151* (2015). The authors of this work include Rebekah Yang, Seunngu Kang, Hasan, Ozer, and Imad-Al-Qadi. Any figures, tables or data not created by the author of this dissertation is indicated within the chapter.

transportation agencies who may consider the risks and tradeoffs involved in environmental impacts when using recycled AC mixtures.

2.2 Background

The use of recycled material in bituminous roadways is not a new concept. Both RAP and RAS are common recycled materials that are used in asphalt mixtures due to the ability of these asphaltic materials to partially substitute the need for virgin aggregates and/or asphalt binder. For an AC mix, the percentage of virgin asphalt binder that is substituted by recycled asphalt binder from RAP or RAS is known as the asphalt binder replacement (ABR) ratio. Asphalt binder is added in small quantities in AC mixtures, typically 4–8% by weight, and it serves as the main adhesive that holds the mixture together. Asphalt binder is a petroleum product that is mainly derived from crude oil and requires a large amount of energy to produce. Although a small component of the overall mixture by weight, binder can contribute highly to the total energy consumption and financial cost of producing an AC mixture. Environmental performance of pavements constructed with AC containing RAP and/or RAS is often expressed in terms of energy and GHG savings at the material production stage due to replacement of virgin materials. While energy and GHGs are only two of numerous other environmental impacts (e.g., acidification, smog, and eutrophication), these two environmental burdens are most often reported in pavement construction analyses because data such as fuel usage for equipment and plant operations are more readily available.

In the U.S., RAP is increasingly being used and the benefits of reduced environmental footprint and lower costs are well understood and applied. According to one study, the amount of RAP used in AC was around 70 million tons in 2013 (Hansen & Copeland, 2013). This represents around 10% of the total AC produced in the US. Asphalt roofing shingles are an abundant material with 11 million tons being landfilled each year in the U.S. (Goh & You, 2011). In general, RAS comes from two main sources: shingles that are rejected by the manufacturer, called manufacturer waste scrap shingles (MWSS), and shingles removed during reconstruction of building roofs, called tear-off scrap shingles (TOSS). Goh and You (2011) noted that MWSS provide only a small amount (9%) of shingles for recycling and use in AC while TOSS are a more plentiful source. One benefit associated with using RAS is that it contains a high percentage of binder which could partially replace the virgin binder, thus lowering both costs and environmental footprint.

In the state of Illinois, one study by Lippert et al. (2014) noted that in 2013, the Illinois Department of Transportation (IDOT) used about 1.7 million tons of recycled materials in highway construction projects. The study further observed a fourfold increase in the amount of recycled material in 2013 over the

amount used in 2009 on a tons-per-mile basis. The study attributed the increase to, among other factors, the expansion of approved RAS processing facilities and tolerances in the specifications.

The environmental benefits of using RAP and RAS are documented in literature, mostly limited to the evaluation of environmental impacts associated with the initial production of AC mixtures. Aurangzeb et al. (2014) examined the environmental footprint of AC mixtures prepared with high RAP content. The authors observed reductions in energy and GHGs of up to 12.2% with mixtures prepared with 50% recycled RAP material. Another study observed up to 7.5% reduction in energy consumption and 13% reduction in GHGs or global warming potential (GWP) (Meli, 2006). A similar study also reported up to 4% reductions in energy consumption and carbon dioxide (CO_2) emissions with the incorporation of 25% RAP and 10% bottom ash in bituminous roadways (Huang et al., 2009). In terms of RAS, one study noted up to 16% reduction in GHG emissions with using mixtures prepared with 20% RAP and 7% RAS (Booz Allen Hamilton, 2013). In general, the environmental performance of AC containing RAP has been more widely studied than those of RAS. However, environmental footprint studies of pavement construction with RAP and RAS show consistent savings in the energy consumption and GHG emissions, mostly due to reductions in the virgin aggregate and asphalt binder production.

One major concerns with the use of recycled materials in pavements is whether an equivalent functional and structural performance will be achieved with pavements containing significant percentages of recycled materials. A large volume of research has been dedicated to investigating the performance of AC mixtures containing recycled materials at both a laboratory and field test scale. Williams et al. (2013) conducted both laboratory and field tests using AC mixtures with different ABR contents at various locations in the U.S. In the laboratory testing, the AC mixtures showed good rutting resistance, fatigue cracking resistance, and fracture properties compared to AC mixtures without RAS. The AC mixes, in the field, showed no signs of rutting, fatigue or thermal cracking, but transverse reflective cracking was observed in Missouri, Colorado, Iowa, Indiana, and Minnesota. Another study by McGraw et al. (2010) reported that RAS sections on U.S. Highway 10 in Minnesota were very brittle in appearance and experienced substantial reflective cracking after the first winter. Ozer et al. (2013) conducted a laboratory study on AC mixtures with different RAS contents (2.5, 5.0, and 7.5%) and virgin asphalt binder (PG 58-28 and PG 46-34). Overall, it was found that fatigue potential increased with increasing RAS content. In addition, using the lighter PG 46-34 binder improved fatigue life and fracture energy, suggesting that a properly modified binder grade should be considered at increasing levels of RAS to possibly address that issue.

In general, there is a consensus that physical and engineering properties of recycled materials are different from those of virgin materials. Such changes or differences in the inherent properties of recycled materials may also result in differences in the performance even if the mix is properly designed and

engineered. RAP and RAS are composed of solid (i.e. aggregate, fibers, etc.) and binder fractions. Characteristics of the solid fraction include source, specific gravity, hardness, and absorption whereas aging level, viscosity, and stiffness constitute major characteristics of the binder fraction. Among these characteristics, properties of the binder fraction of recycled materials have a great influence on the overall strength and fracture behavior of AC mixes. There are many factors that can affect the performance of pavements, and it does not seem there is a consensus on the performance of AC pavements containing RAP and RAS at this point due to lack of field performance data. However, it is imperative that a scenario-based analysis be conducted to evaluate such benefits and tradeoffs introduced by using more recycled materials in pavements.

2.3 Objective

The objective in this chapter is to conduct a sustainability evaluation of flexible pavements constructed with recycled contents (RAP and RAS), with the ultimate goal of providing an objective guidance to agencies aimed at evaluating the benefits and risks of using more recycled materials in their pavements. The sustainability metrics considered are agency costs and environmental performance throughout the life-cycle of a flexible pavement. Environmental performance is represented by energy consumption and GWP in this study. High quality inventory data for initial cost and environmental impacts were coupled with a scenario-based assessment for the expected future pavement performance.

2.4 Methodology

2.4.1 Goal of the study

The goal of this study in this chapter is to quantify the life-cycle environmental performance of a typical overlay constructed with AC mixtures containing various amounts of RAP and/or RAS, and to compare environmental savings from using these recycled materials with additional environmental effects based on expected performance. The AC mixtures in this study are from recent construction projects found in Illinois. A scenario-based approach was applied where traffic and performance expectancy varied in addition to RAP and/or RAS percentages in AC mixtures.

2.4.2 System boundaries and analysis period

For pavements, there are typically considered to be five life-cycle phases: material acquisition/production, construction, use, maintenance, and end-of-life (EOL). The analysis period of the study is assumed to be 15 years, representing the typical design life of a well-performing AC overlay. The initial construction of all AC mixtures is assumed to be the same, and no agency interference via rehabilitation is considered.

Thus, the scope of the study in this chapter is limited to only the material and use-phases of asphalt overlays using AC mixtures with different ABR as depicted in Figure 2.1. By using comprehensive commercial LCI databases, the study accounts for the environmental impacts from upstream processes such as production of fuel and electricity.

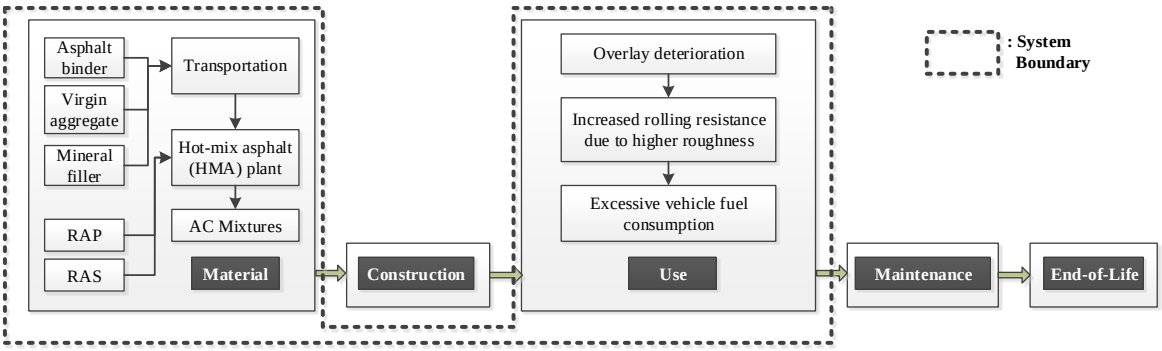


Figure 2.1: Pavement life-cycle phases and system boundary (Yang et al., 2015).

2.4.3 Functional unit

The functional unit of this study is four-lane-miles of a 4-inch asphalt overlay expected to last 15 years by satisfying design and performance criteria in Illinois. The deterioration is measured with respect to International Roughness Index (IRI), which represents a standardized pavement unevenness obtained by a response-type road roughness measurement system (Sayers et al., 1986). The relationship between pavement smoothness and extra fuel consumption of vehicles are well established in the literature (Chatti & Zaabar, 2012; Van Dam et al., 2015; Sandberg, 2011). The predicted excessive fuel consumption can then be compared to the energy savings from producing mixtures with RAP and RAS to find a breakeven point indicating the balance at which extra fuel consumption due to faster deterioration of pavement negates upfront savings achieved by using recycled materials. The scenarios to find the breakeven point assumes overlays with varying degrees of deterioration as compared to a baseline (well-performing) overlay.

2.4.4 Data and data quality requirements

The inventory data (input and output flows associated with production of an overlay) for LCA are grouped into categories: primary and secondary. Primary data are those specific to the production processes for the product assed, while secondary data represents generic or average data for the product. In general, regionalized secondary data were used in most of the unit processes while primary data were collected for some production processes as well as for the mix designs themselves. According to ISO 14044, a unit process is “smallest element considered in the life-cycle inventory analysis for which input and output data are quantified” (ISO, 2006b). The unit processes were gathered using various sources spanning commercial

databases, publicly available reports and papers, and nationwide statistics. Information concerning plant and facility operations, fuel usage, and production were also collected from material producers, plant operators, and contractors from the Northern Illinois area in 2012-2013 (Kang 2013). As the focus of the study is overlay production, unit processes describing AC plant production were modeled to be representative of overlay in Illinois. When secondary data is used, the input-output flows can be obtained combining primary data collected (plant production energy consumption, production rate, equipment usage, etc.) with emission factors obtained from other sources.

ISO 14044 recommends that a number of data quality requirements be addressed to ensure that LCI data used in the LCA are appropriate and relevant to the goal and scope. The AC mix designs evaluated in this study are selected from another experimental study by the Illinois Center for Transportation with a focus on determination of engineering properties of recycled AC mixtures. These mix designs are designed according to specifications used in Illinois with representative materials. Furthermore, the secondary LCI data used in this LCA are representative of Illinois processes pertaining to time-related, geographical, and technological coverage. In general, the LCI used activity data from local sources whenever possible with inventory data coming from commercial LCI databases such as US-Ecoinvent 2.2 (US-EI 2.2). Using comprehensive commercial LCI databases with SimaPro, a LCA software, ensures that upstream processes are captured. Local data was obtained both from publically available databases and sources as well as from surveys that were distributed to industry contacts in 2012–2013 regarding environmental data for the production of various pavement materials (Kang, 2013; Kang et al., 2014). For an example of time-related and geographical coverage, the LCI for asphalt binder production is taken from a model that reflects 2005–2012 crude oil sources and refining fuels from the Midwest region where Illinois is located (Yang, 2014; Yang et al., 2016). An example of technological coverage is found in the AC plant model, to be discussed later in this chapter, which considers the realistic effect of moisture content from recycled materials on energy usage.

2.4.5 Inventory analysis

A summary of the data collection and calculation procedures of major unit processes relevant to AC mixtures are given in this subsection.

In the mixtures examined, four main types of aggregates exist: crushed stone (e.g. CM11, CM16), crushed gravel (e.g. CM13, CM14), manufactured sand (e.g. FM20, FM22), and natural sand (e.g. FM01). In Illinois, crushed stone and manufactured sand are typically obtained from limestone quarries. Blasted rocks in quarries are further crushed one or more times to obtain aggregates of different sizes. Crushed gravel and natural sand can be dredged from river beds and crushed, if appropriate, to obtain desirable aggregate gradations. LCI data from local aggregate producers were not available, so inventory and

environmental impact information associated with the production of aggregates were obtained from unit processes in the US-EI 2.2 database. These processes were modified with local Illinois electricity and hauling processes to better represent the scope of the study. Crushed stone and manufactured sand were represented by the same crushed limestone unit process, while crushed gravel and natural sand were represented by dredged crushed gravel and sand unit processes, respectively.

In this study, a cut-off allocation (also known as the recycled content method) is used to account for the production of recycled materials. According to this method, the system using the recycled materials receives the benefit because the recycled materials replaces virgin materials. Thus, recycled materials enter the system boundary without a burden and credit. The only environmental burden of RAP and RAS are associated with processing of these materials (i.e. crushing, screening, stockpiling) in the AC mixture production plants. Therefore, system boundaries have been drawn to exclude removal activities from the previous product's EOL (i.e. milling or removing and transportation to AC plant) so that only the post-processing of these materials is considered. Based on questionnaire survey responses from Northern Illinois manufacturers, the crushing and screening of these recycled materials were modeled to generate inventory data for RAP and RAS.

To model the production of asphalt binder, an existing regional inventory model corresponding to the U.S. Midwest region is used (Yang, 2014; Yang et al., 2015). A representative model is especially important for binder due to the large variance in crude oil sources and refinery fuels that are used in U.S. refineries. The model used considers crude oil extraction and flaring, oil transportation, oil refining, asphalt binder transportation, and asphalt binder storage. An economic allocation is used in oil refining to determine energy requirements needed to refine asphalt binder among multiple refinery outputs.

The raw materials described previous are ultimately transported to an asphalt plant and combined. The handling, mixing, and heating of raw materials is a significant process in AC mixture production, and the energy consumed and GHGs emitted at a plant varies depending on the type of mixture being produced. Thus, a variable model[2] was used in order to capture changes in environmental impacts from different types of AC mixture. While an asphalt plant has numerous components such as mixers, conveyor belts, fans, and wheel loaders that consumer electricity and diesel, the majority of energy consumed at a plant is spent on drying aggregate and mixing/heating the raw materials. In Illinois, drum mix plants are typically used and natural gas is the predominate fuel used for drying, mixing, and heating in the drum (Lippert et al., 2014).

The plant model used in this study included static values of diesel fuel use by in-plant loaders and electricity use for conveyors and other supporting components from locally collected data. For the drum, the energy consumption for drying and mixing is sensitive to mixing temperature and the moisture content

[2] This model was developed by Seunggu Kang.

of aggregates and recycled materials. Mixing temperature is one feature that separates hot-mix asphalt (HMA) from warm-mix asphalt (WMA). Moisture content can be affected by the types of aggregate and recycled material used in the mixture. For example, RAS typically has a higher moisture content than virgin aggregate and RAP because water is generally added while grinding shingles and the resulting RAS particles, as would be expected, have higher surface area than the aggregate (Huber and Lippert, personal communication, March 4, 2015). Thus, in order to take into account the effects of temperature and moisture content, Equation (2.1) was used to model the amount of natural gas used per ton aggregate produced, where Y is the drying energy in British thermal units, X_1 is moisture content of aggregate (%), and X_2 is temperature at final discharge (ºF).

$$Y = 26352.77X_1 + 537.98X_2 - 32598.9 \qquad (2.1)$$

The estimated changes in energy consumption are based on linear energy savings reported by the National Asphalt Pavement Association (Young, 2008). For the mixtures with RAS analyzed in this study, it was assumed that the moisture content of RAP and virgin aggregate were 5% and that of RAS was 15%.

2.4.6 Impact assessment

Two environmental metrics were considered in this analysis: GWP and cumulative energy demand (CED). The U.S. Environmental Protection Agency (EPA)'s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 was used to calculate GWP for all relevant unit processes. An energy indicator, CED, was also calculated for all relevant unit processes. This metric includes all upstream and primary energy used for fuel required for each unit process. Energy stored inherently in materials not used as fuel, such as that in the petroleum product of asphalt binder, is not included in this chapter. This energy is measured as feedstock energy and defined by ISO 14040 as the "heat of combustion of a raw material input that is not used as an energy source to a product system" (2006). The analyses presented are limited in that they only examine GWP and CED. Thus, any conclusions made in the environmental analyses presented can only be applied to GWP and CED; no other environmental impacts have been evaluated at this point.

2.5 Case Study

Four-lane-miles of a 4-inch AC overlay pavement was used in the case study along with eleven AC mixtures with varying contents of RAP and RAS. The first part of the case study evaluates the environmental performance of producing a cubic yard of these mixes to define the range of initial cost and environmental savings possible from various ABR mixes. A preliminary analysis of the mixes used in this study were

conducted previously to illustrate environmental savings during the mix production stage, without consideration of aggregate moisture effect on plant operations, the quality of aggregates or the use-phase (Yang et al., 2014).

The second part of the case study uses a scenario-based approach to estimate the life-cycle impact of using RAP and/or RAS in overlays. Deviations from a well-performing overlay (with service life of 15 years until the next major rehabilitation) are simulated with varying degrees of smoothness deterioration under different traffic conditions. The goal is to generate a set of scenarios where IRI progresses at varying rates (slower or faster rate than a well-performing overlay) until the end of 15 years in order to determine the extra fuel consumption due to additional IRI for each scenario. Only the material production and use-phases are considered; it is assumed that the impacts from construction are the same and the analysis period is chosen as 15 years to avoid additional rehabilitations that would interfere with IRI progression. The environmental impacts for material production and associated assumptions used in the study were discussed in the methodology while a description of the mixes analyzed, the cost parameters, and the models and assumptions applicable to the use-phase are presented in this section.

2.5.1 Mix descriptions

A description of the eleven AC mixtures used in this study can be found in Table 2.1. The mixtures range from having 0–8% RAS and 0–50% RAP, resulting in a total ABR range from 0–60%. The control AC mixture, Mix 1, has 0% RAS and 0% RAP.

Table 2.1: Mix Volumetric and Design Details

Mix	Mix ID	NMAS (mm)	% Total Binder	% ABR	% RAP	% RAS	% Voids	G_{mb}[3], Design	Transport (ton-mi)
Mix 1	N90-00	19.0	5.2	--	--	--	4	2.398	54
Mix 2	N70-25	9.5	6.0	25	29	--	4	2.389	40
Mix 3	N80-25	12.5 SMA	6.1	26	8	5	3.5	2.405	107
Mix 4	N90-26	19.0	5.2	26	30	--	4	2.397	39
Mix 5	N90-33	19.0	5.2	33	40	--	4	2.401	33
Mix 6	N70-38	9.5	6.4	39	30	5	4	2.387	36
Mix 7	N90-41	19.0	5.2	41	50	--	4	2.405	28
Mix 8	N70-50	9.5	6.0	48	30	5	4	2.383	36
Mix 9	N50-50	19.0	5.5	49	42	4	3	2.424	31
Mix 10	N80-50	12.5 SMA	6.0	50	10	8	3.5	2.405	101
Mix 11	N50-60	19.0	5.6	59	42	6	3	2.424	29

Among the mixes, three are surface courses with nominal maximum aggregate size (NMAS) of 9.5 mm while the remaining eight are binder courses with NMAS of 12.5 and 19.0 mm. In addition, Mixes 3 and 10 are stone mastic asphalt (SMA) mixtures, which require high quality crushed gravel instead of crushed

[3] G_{mb} stands for bulk specific gravity.

limestone as well as higher asphalt binder content for mixes having same NMAS. Typical Illinois transportation distances for material to plant were found to be 60 mi for binder, 25 mi for crushed stone aggregate and sands, 50 mi for crushed gravel aggregate, and 0 mi for RAP, RAS, and mineral filler. Also, the asphalt binder for each of these mixtures are assumed to have the same environmental and economic impacts. While the SMA mixes should not be compared directly to dense-graded mixes due to differences in functional role, these are included in this analysis as a reference.

2.5.2 Agency cost

The economic cost to the funding agency for raw material acquisition and production of the AC mixtures, mirroring the boundaries of the initial environmental evaluation, is also considered in this study. Additional costs such as design, transportation to site, laydown, administration, safety, etc. are not considered. Average 2013 Illinois prices for various pavement materials have been obtained from reports and online databases (IDOT, 2013; IDOT, 2015; Lippert et al., 2014) maintained by IDOT as well as input from local experts and are compiled in Table 2.2. Average or best estimate costs are used in some cases as aggregate prices vary depending on size and quality and asphalt binder prices fluctuate depending on the oil market. In addition, it is assumed that mineral filler is a by-product that requires negligible processing costs. A blanket transportation rate is estimated for all material-to-plant transportation needs, and the same plant production cost is given to each plant that is approximately 1/7 of the average material production costs (Copeland, 2011).

Table 2.2: Illinois 2013 Average Prices for Various Asphalt Paving Materials

Material	Aggregate Type[4]	Cost per ton
Asphalt Binder	--	$500.00
RAS	--	$42.50
RAP	--	$33.10
Crushed Stone for Surface Mixes	032CM16	$21.00
Crushed Stone for Binder Mixes	042CM11	$17.00
Crushed Gravel for SMA Surface Mixes	031CM14	$22.00
Crushed Gravel for SMA Binder Mixes	031CM13	$19.00
Natural Sand	037FM01	$10.00
Manufactured Sand	038FM20/22	$13.00
Mineral Filler	--	$0.00
Transportation for all materials (per ton-mile)	--	$0.30
Plant Production		$12.00

[4] *For IDOT aggregates, the material code ("###CM##") designations are as follows: first "##" indicates quality, where 02=A quality, 03=B quality, 04=C quality, 05=D quality; the following "#" is stone type, where 1=crushed gravel, 2=crushed stone, 7=natural sand, 8=manufactured sands; CM/FM for coarse or fine aggregate; and the last "##" specifies the gradation.

2.5.3 Use-phase

The use-phase of the pavement life-cycle has often been omitted from pavement LCAs due to its complexity, even though it is known to contribute immensely to the total environmental impacts incurred throughout the pavement life-cycle. The use-phase includes strictly pavement-related effects such as albedo and carbonation as well as effects related to vehicle-pavement interaction. The latter influences vehicle fuel consumption and resulting emissions due to pavement surface roughness, macrotexture, and deflection. In this study, only pavement surface roughness as represented by IRI will be considered, as extra fuel consumption due to IRI has been shown to contribute largely to use-phase emissions (Yu and Lu, 2012; Santero et al., 2011; Wang et al., 2012) and models for this effect are readily available. Two models are needed to evaluate the impact of roughness on the use-phase, one to describe IRI progression over time and another to determine the IRI-fuel consumption relationship.

Over time, the surface roughness of a pavement will deteriorate due to aging, climate, and traffic loading. Using a regression-based IRI progression model developed internally, the yearly increase in IRI is predicted over the 15 year analysis period based on pavement surface thickness and annual traffic. An example IRI progression curve (A) is given in Figure 2.2 for an ADT of 60,000 vehicles with 20% truck traffic. An initial IRI of 60 inch/mile is assumed and the pavement roughness increases by approximately 6 inch/mile each year until it reaches 149 inch/mile at 15 years after construction. The IRI progression resulting from this model is assumed to represent a baseline or well-performing pavement. A poor-performing overlay (B) on Figure 3 would have a steeper IRI curve while a superior-performing overlay (C) would have a shallower IRI curve than that of the well-performing overlay (A).

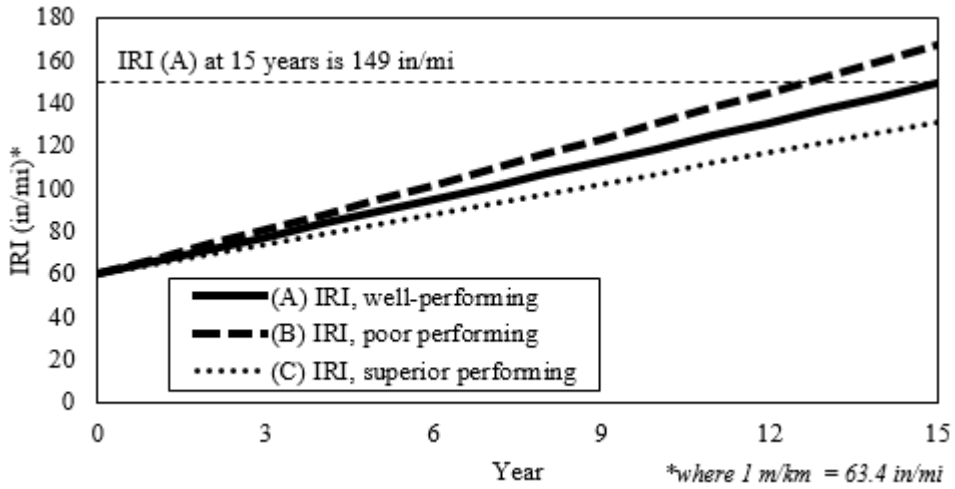


Figure 2.2: Example IRI progression model for 60,000 ADT.

The relationship between increasing surface roughness and increasing vehicle fuel consumption has been estimated by various studies. For example, using field tests, Chatti and Zaabar (2012) found that a 63.4 inch/mile (1 m/km) increase in IRI will result in a 1-2% increase in fuel consumption for passenger cars and trucks. In addition, Wang et al. (2012) and Ghosh et al. (2015) used models to describe the relationship between IRI and rolling resistance force from the World Bank's Highway Development and Management Model (HDM-4) to model vehicle emissions with EPA's Motor Vehicle Emission Simulator (MOVES). The models from Ghosh et al. (2015) detailing the relationship between change in IRI and extra fuel consumption for various vehicle types are used in this study. According to this relationship, a 63.4 inch/mile (1 m/km) increase from 60 to 123.4 inch/mile (0.95 to 1.95 m/km) in IRI will result in a 3.7% energy increase for passenger cars, 1.2% for small trucks, 1.3% for medium trucks, and 0.9% for large trucks.

2.6 Environmental Analysis

The percent distributions of total energy consumption and GWP for each process necessary in producing a similar volume of each mix are shown in Figure 2.3.

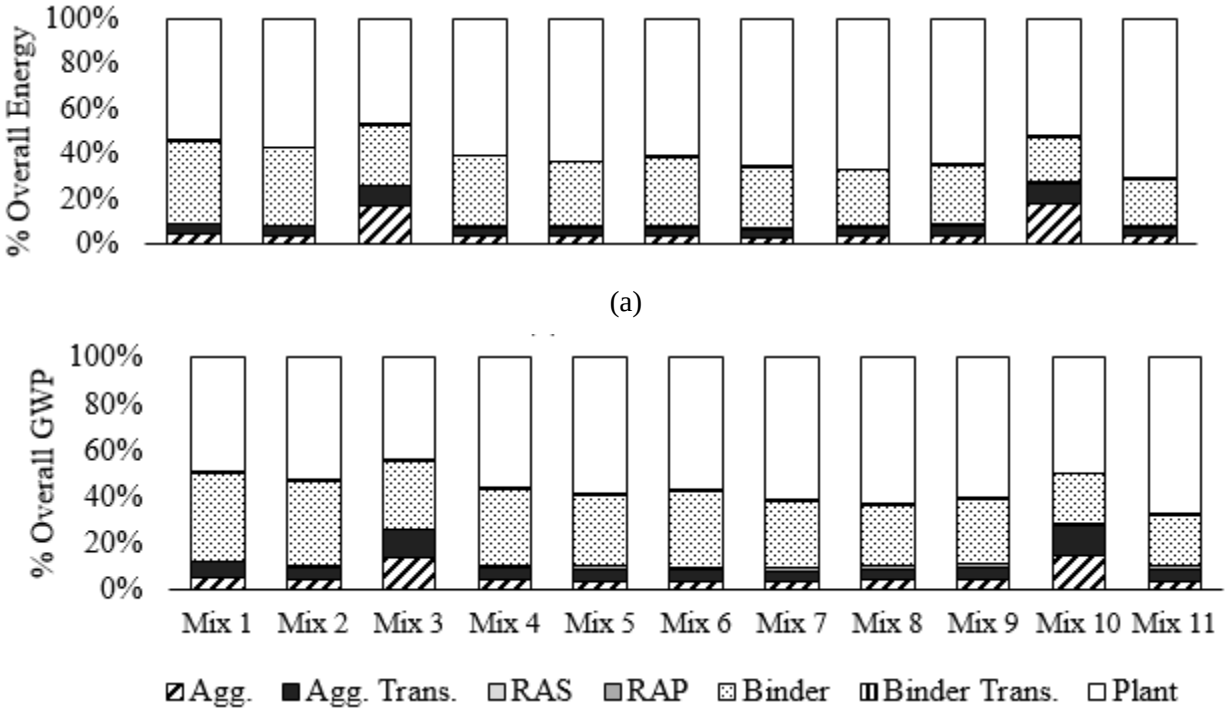


Figure 2.3: (a) Energy and (b) GWP breakdown of the contribution of each process to each mix.

Major contributors to GWP and energy consumption are plant operations, binder production, and aggregate production and transportation in decreasing order. In general, as the recycled content increases from Mix 1 to 11, the relative contribution of plant processing increases from the lowest at 47% to 71% for energy and 44% to 67% for GWP. This reflects both the use of less virgin materials as well as slight increases in plant fuel usage due to the inclusion of more RAS at higher recycled contents. As expected, the energy and GWP from each process are similar, with both showing that RAS processing, RAP processing, and binder transportation together contribute an average of less than 2% of the total energy and GWP from producing the mixes. Finally, Mixes 3 and 10 both show larger aggregate environmental contributions than the other mixes due to the higher production and transportation impacts from crushed gravel that is used in these SMA mixes.

When comparing the ten AC mixtures with recycled content to the control mix produced only using virgin materials, there are clear reductions in energy and GWP indicating a consistent trend. In Figure 2.4, it can be seen that the highest environmental reductions occur with Mix 11 (42% RAP, 6% RAS), which incurs 80% of the energy and 78% of the GWP of Mix 1. A clear trend can be seen also for decreasing energy and GWP with higher ABR due to the reduction in virgin asphalt binder used in the mixes.

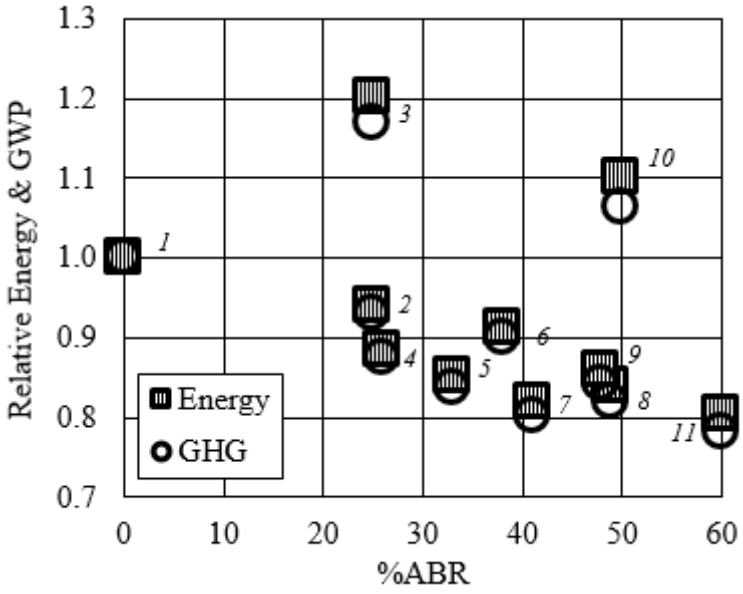


Figure 2.4: Relative energy, relative GWP, and ABR content for each mix (mix numbers corresponding to Table 2.1 are shown on the figure).

The relative environmental impacts for the SMA mixes (Mix 3 and 10) are above the general trend shown by the dense-graded mixtures. The SMA mixes contain a higher percentage of RAS and higher quality aggregates than their dense-graded counterparts, which in turn increases the amount of virgin

aggregates and environmental burdens required. In addition, SMA mixes are often more costly than dense-graded mixes and are also expected to perform better than the latter. The SMA mixes both have higher energy and GWP impacts than the control mix, which implies that these two categories of mixes should not be directly compared. It is not appropriate to simply compare mixes with varying amounts of recycled material, rather, the SMA mixes with recycled material should be compared to virgin SMA mixes to allow for better comparison. Nonetheless, observing the decreasing environmental impacts from the higher to lower SMA mixes, it is implied that a similar trend for dense-graded and SMA mixes with increased recycled content is likely.

2.7 Economic Analysis

An initial cost analysis was also performed for the eleven mixes using average 2013 Illinois costs from Table 2.2. Figure 2.5 shows the relationship between cost, energy, and ABR per cubic yard of each mix, with the two SMA mixes labeled 3 and 10. Two trends can be observed in this figure: decreasing cost with increased ABR content and increasing cost with increased energy. The SMA mixes are again set apart from the dense-graded mixes due to the higher costs of the crushed gravel they contain. In addition, surface mixes generally have a higher binder content and higher cost, leading to the 25% ABR surface mixture (Mix 2) having a slightly higher cost than the control mix, which is a binder mix.

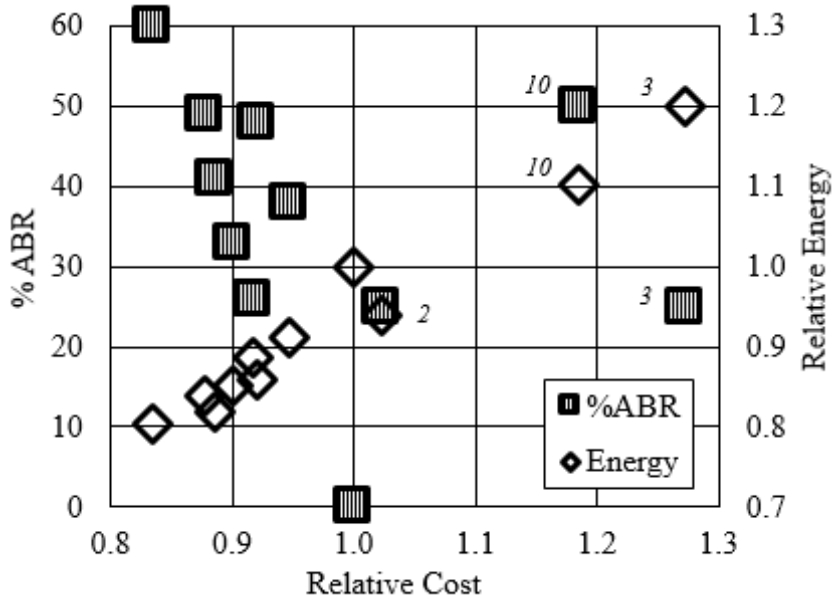


Figure 2.5: Relative cost, relative energy, and ABR content for each mix (labels added for Mixes 2, 3, 10).

2.8 Use-Phase Scenarios

The environmental and economic analysis given above addresses only the material production phase of the pavement life-cycle. If all eleven mixes are assumed to perform equally well, the remaining life-cycle phases can be assumed to be the same and the LCA analysis can be cut-off at the first phase. However, if it is unknown whether the mixes will perform equivalently, then other phases of the life-cycle must be considered. In this study, various performance scenarios for a mixture with recycled content and their corresponding effects on environmental impacts are investigated.

The service life of a well-performing, baseline overlay is assumed to be 15 years. If the mixture performs poorly, the pavement will deteriorate faster. There are two potential consequences of this. First, the service life will be shorter and may require rehabilitation prior to 15 years incurring additional costs for the agency. Second, the agency does not interfere regardless of the condition of pavement and users bear the burden by traveling on rougher roads. Pavement deterioration is represented by IRI in this case study, and, to maintain a consistent analysis period, it is assumed that no agency interference occurs prior to 15 years even if excess pavement deterioration occurs. Thus, users bear the burden and due to increased IRI, additional fuel will be consumed by vehicles over 15 years on the same overlay mixture if it is poor-performing as compared to if it were well-performing. This extra fuel consumption due to pavement performance is taken to be the environmental impacts from the use-phase of the life-cycle. At some point, the extra fuel will offset any environmental or energy savings from the material production phase. The level of pavement performance at which this occurs can be represented by a "breakeven" service life, as first used by Aurangzeb et al. (2014). It should be noted that the breakeven service life can also be greater than 15 years if the performance of the evaluated overlay is better than the baseline overlay performance as predicted in the IRI progression model.

Figure 2.6 demonstrates the breakeven performance concept used in this study. Assuming an ADT of 10,000 vehicles with 20% truck traffic and an initial post-construction IRI of 60 inch/mile. The IRI at which the well-performing overlay reaches at 15 years is 130 inch/mile, while the poor-performing overlay reaches this IRI value at 12.4 years. The extra fuel consumption incurred by the latter over the 15-year analysis period is equivalent to 0.83 TJ of energy, which is incidentally equal to the energy savings from Mix 11 with 60% ABR as compared to the control mix. Thus, the breakeven service life for this particular mix, traffic level, and performance scenario is approximately 12.4 years. If the overlay performs worse than a 12.4 year service life, the environmental burdens from the use-phase will outweigh the environmental savings from material production.

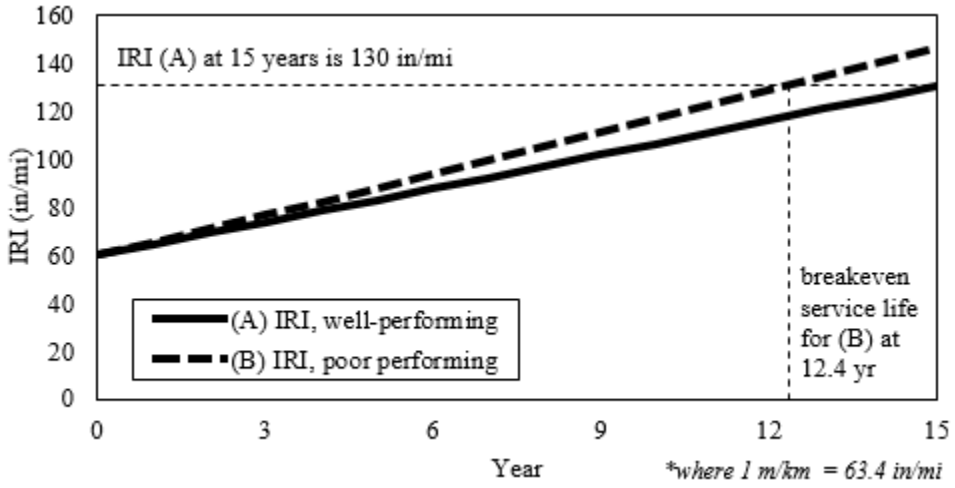


Figure 2.6: Breakeven service life for Mix 11 with 10,000 ADT.

As the magnitude of the environmental burdens from the use-phase are dependent on traffic level, the breakeven service life is also highly dependent on traffic level. In Figure 2.7, the net energy savings from producing four-lane-miles of 4-inch overlays with varying amounts of recycled contents are shown. All of the overlays contain the same 2-inch surface course with 30% RAP, 5% RAS (Mix 9), but different 2-inch binder courses with increasing amounts of RAP (Mix 1, 4, 5, 7 corresponding to Overlay A, B, C, D). Thus, Overlay D gains the most energy savings due to its high recycled content (Mix 7 and Mix 9). The predicted energy contributions from the use-phase only are also shown for low traffic scenarios with an ADT of 6,000 and high traffic scenarios with an ADT of 60,000. For each traffic level, scenarios assuming lower performance (i.e. service life under 15 years) show energy burdens from additional roughness-related fuel consumption, while scenarios assuming a higher performance (i.e. service life above 15 years) display energy savings from reduced fuel consumption.

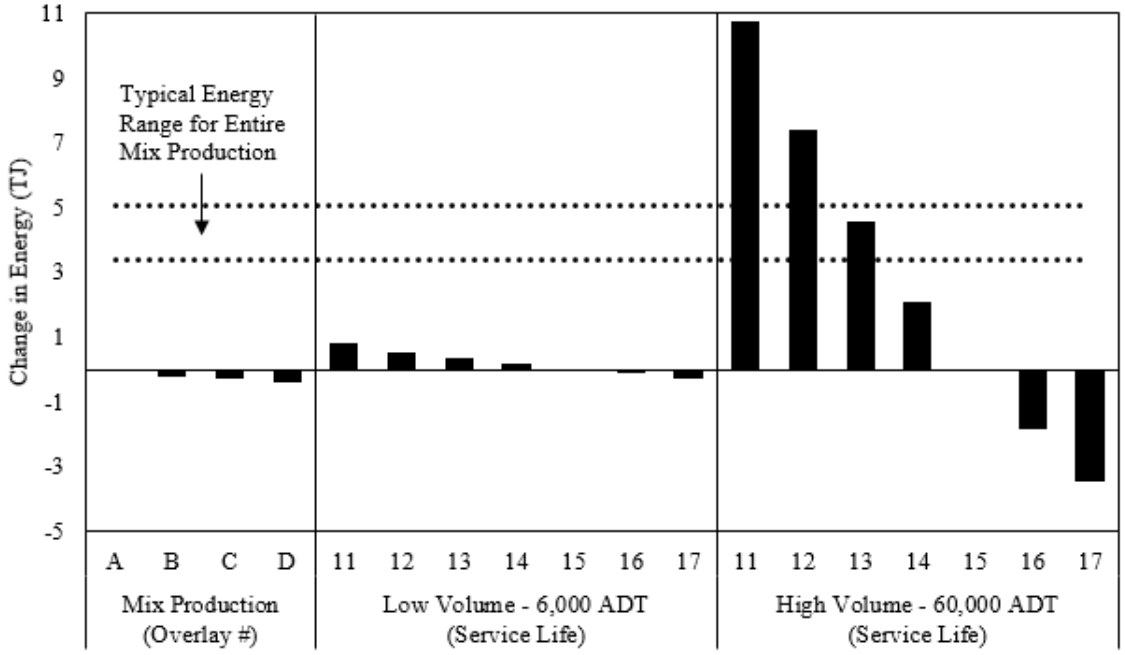


Figure 2.7: Energy burdens (+) and savings (-) for material and use-phases with different service lives and traffic volumes.

The use-phase energy from the high traffic scenarios is greater than the energy savings from mix production when the service life is increased or decreased by only one year. When the pavement performance deviates more than one or two years from the expected service life of 15 years, the use-phase energy overwhelms the initial energy savings. On the other hand, the use-phase energy from the low traffic scenarios do not exceed Overlay D's mix production savings until the service life is below 13 years. Figure 2.7 also shows the range (in dotted lines) of total energy consumption needed to produce four-lane-miles of the mixes considered in this study. At the higher traffic level, the extra energy consumption from the use-phase is comparable to the energy requirements of the entire material production phase when the service life drops below 13 years. Thus, once the service life falls below 13 years, no amount of energy savings from mix production would be able to offset the additional energy incurred by the use-phase.

Furthermore, Figure 2.8 presents a generalized relationship between breakeven service life, ADT, and energy burdens or savings from the use-phase. At a constant reduced performance or service life, as ADT increases, the additional energy burdens incurred by the use-phase increase dramatically. In another interpretation, at the same energy level, the breakeven service life increases rapidly with increased ADT. Conversely, the energy savings from the use-phase also increase rapidly with increased ADT at a higher performance or service life. Thus, at high traffic volumes, the environmental impacts from the use-phase overshadow that from the material production phase.

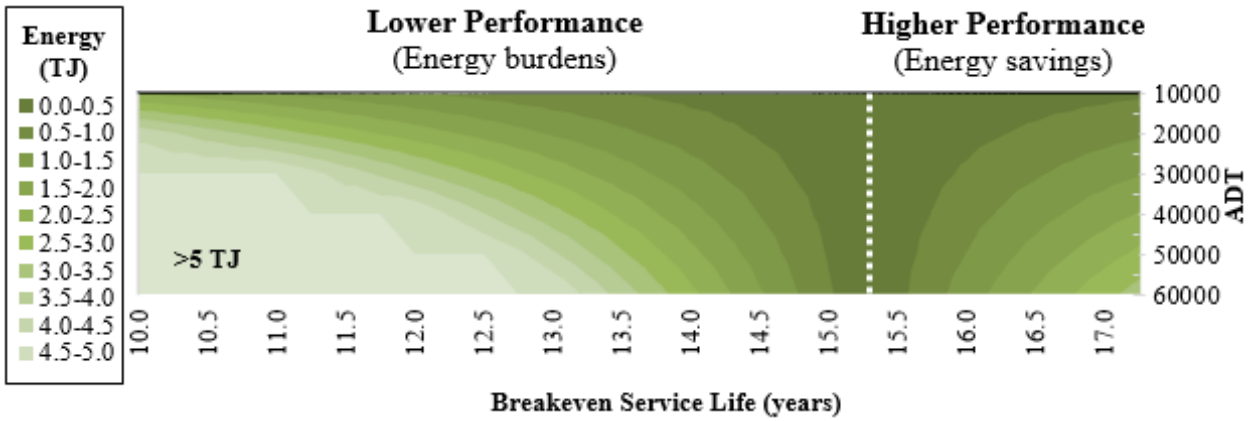


Figure 2.8: Energy burdens and savings for different breakeven service lives and ADT.

The scenarios described assume a predicted progression of IRI within a constant analysis period without any agency intervention. In reality, depending on the severity of the roughness and the agency budget of, additional rehabilitation may be performed, lowering the IRI and thus affecting the extra fuel consumption. Thus, the results shown in this analysis represent an extreme (worst) case, where agency intervention is not considered and consequent reductions in roughness-related impacts after the intervention are not taken into account. This analysis is limited in that the analysis period is only as long as the expected service life of the first overlay. In order to evaluate a more comprehensive set of life-cycle impacts, an analysis period spanning multiple rehabilitations may be considered. With such an analysis, parameters such as traffic growth and volume will be crucial factors in vehicle fuel consumption that may also warrant evaluation using sensitivity analyses. A comparison of scenarios considering agency intervention should be performed in the future, with careful consideration to the analysis period used.

2.9 Summary

The purpose of the study in this chapter was to evaluate the life-cycle environmental impacts and initial economic impacts of flexible pavements constructed with varying amounts of recycled materials (RAP and RAS). The goal and scope, inventory analysis, impact assessment, and interpretation of the LCA study were documented in accordance with ISO 14044:2006 guidelines where possible.

In the first part of the study, the production of 11 overlay AC mixtures were evaluated with respect to energy consumption and GWP. In general, when comparing ten mixtures with 25–60% ABR to a virgin dense-graded mixture, the relative energy, GWP, and cost decreased with increased recycled content. Notable points in the trend that exceeded one or more of the sustainability metrics of the control mixture were the SMA mixes that required higher quality crushed gravel and more asphalt binder.

The second part of the study considered the environmental performance of the overlay over an analysis period of 15 years using a scenario-based assessment. The concept of a breakeven point was used, where the extra fuel consumption due to increased IRI of a reduction in overlay performance was equal to the energy savings in the material production phase. The difference in fuel consumption was calculated based on the IRI progression of a well-performing pavement with a service life of 15 years, and the breakeven point was represented by the service life of a potentially poor/superior-performing pavement. It was found that the breakeven point was highly dependent on the traffic level of the overlay. The breakeven service life increased sharply with increased traffic when considering the same energy savings. At high traffic levels, the energy burdens from the use-phase were able to overshadow the energy savings from the material production phase with a small decrease in service life.

Overall, a sustainability framework was introduced along with a case study for agencies to reference as they evaluate the advantages and disadvantages of increasing the amount of recycled content in their flexible pavements. To achieve that, extensive data collection and modeling were conducted to produce a regional inventory database for use in the environmental impact analysis. In addition, a scenario-based analysis was used to demonstrate an approach for agencies to assess potential risks and tradeoffs in initial savings and future pavement performance when using recycled asphalt mixtures.

CHAPTER 3

QUANTIFYING SUSTAINABLE STRATEGIES FOR HIGHWAY PAVEMENT CONSTRUCTION[5]

3.1 Motivation

The effects of using recycled material in AC mixtures were examined in Chapter 2 with the use of a regional inventory database and scenario-based analysis; however, recycled AC mixtures are only one of various strategies that can be used to address the sustainability of a pavement system. In this chapter, the inventory database is expanded and a framework is established to systematically analyze a large collection of asphalt and Portland cement concrete (PCC) mixes and pay items related to pavement construction. While previous studies have assessed pavement systems for environmental impacts, they are typically done at the project-level and for one or a limited number of case(s). By establishing a framework for assessing mixes and pay items, a large quantity of data can be analyzed to show trends and variations in environmental impacts over a large sample. Furthermore, the cost of these mixes and pay items can also be obtained and analyzed alongside environmental impact. Using both of these sustainability indicators, the cost-effectiveness of various sustainable strategies are also developed in this chapter. These parameters will be useful to agencies who are interested in the tradeoffs between cost and environmental benefit of common pavement practices and techniques that may be considered sustainable.

3.2 Background

There are a myriad of different approaches focusing on design, materials, and construction that have been used to improve the sustainability of a pavement system. The strategies considered in this study are general construction and material-related practices for the upper pavement layers in the U.S., not including specific design, maintenance or preservation methods.

One common sustainable strategy is the use of recycled materials in pavement structures. The use of RAP and RAS is a typical occurrence in asphalt concrete (AC) pavements. Millions of tons of RAP and

[5] The work in this chapter has been published as "Quantifying sustainability strategies for the construction of highway pavements in Illinois" in *Transportation Research Journal Part D, 51, 1–13* (2016). The authors of this work include Hasan Ozer, Rebekah Yang, and Imad Al-Qadi. All figures, tables, and data in this chapter were created by the author if this dissertation.

RAS are available every year in the U.S., and a number of studies have been conducted to assess the environmental and economic benefits of using RAP and RAS in AC mixtures. For example, one study found reductions in the energy consumption needed to produce recycled asphalt mixes of up to 12.2% when using 50% RAP (Aurangzeb et al., 2014). Another study found an energy savings of 16% when using a mix with 20% RAP and 7% RAS (Booz Allen Hamilton, 2013). Economic benefits from using recycled materials have also been reported by various state agencies, such as the IDOT which determined that $58 million in savings were achieved by the state in 2013 due to the use of 1.7 million tons of recycled materials (Lippert et al., 2014). Out of this tonnage, approximately 40 thousand tons of RAS and 700 million tons of RAP were used.

Secondary material are also incorporated into mix designs for PCC pavements. Ground granulated blast furnace slag (GGBFS) and fly ash are industrial by-products of steel and coal production, respectively. These products are secondary cementitious material (SCM) that can reduce the need for Portland cement in PCC. The environmental benefits of using GGBFS and fly ash have been found to reduce GHG from the production of concrete mixes by up to 17% with 20% fly ash, 43% with 50% GGBFS, and 36% when 40% GGBFS and 30% fly ash are used together (Prusinski et al., 2006; Thomson, 2008). The economic benefits of replacing Portland cement with SCMs are realized when comparing typical unit prices of GGBFS ($65/ton) and fly ash ($20/ton) with that of virgin cement at approximately $80–90/ton (Lippert et al., 2014; Statistica, 2015).

A widely accepted construction technology associated with asphalt pavements is the use of WMA instead of traditional HMA concrete. WMA uses additives or foaming techniques to enable significantly lower temperatures during the production and laying of asphalt. The lower temperatures reduce fuel consumption as well as volatile organic compound emissions. Studies have shown that a 20–50% reduction in plant energy can result in 5%–18% energy savings in the total energy needed for the production and placement of WMA as compared to HMA (Zaumanis, 2010). Similarly, it was found that the use of WMA may reduce GHGs by 3.5% and air pollution by 24% (Hassan, 2010). Some caveats of using WMA may be the extra environmental burden of producing WMA additives and the extra costs of plant modification, licensing, and additives (Zaumanis, 2010).

Another sustainable construction technique is the use of two-lift concrete pavement. A two-lift pavement generally consists of a higher quality upper concrete layer and a lower quality lower concrete layer constructed in two lifts. As part of a multi-billion-dollar effort beginning in 2011 to improve its network, the Illinois Tollway investigated the use of composite jointed concrete pavement using fractionated recycled asphalt pavement (FRAP) in the bottom layer (Gillen et al., 2012). Testing found that up to 50% replacement of FRAP for virgin coarse aggregate is viable within IDOT strength requirements,

with cost analyses showing no economic detriment. Comprehensive environmental studies of two-lift pavement have not yet been widely published.

The sustainable strategies considered in this study are limited to those mentioned above: the incorporation of recycled materials and industrial by-products into AC and PCC pavements, the use of WMA for asphalt pavements, and the construction of two-lift concrete pavements. Numerous other sustainable strategies can be considered for pavement construction (e.g., use of recycled aggregates in bases, more efficient equipment and machinery) but are out of the scope for this study.

3.3 Objective

This study aims to assess the environmental and economic impacts of different mix designs and pay items used in pavement construction. Studies evaluating environmental impacts for specific pavement mixes have been published as well as studies on individual pavement construction projects; however, the systematic environmental analysis of a large sample set of mixes and construction activities has not yet been presented. While pay items are the reference unit for the pavement industry, they are not commonly used as a basis for environmental analyses. An exception to this is the Greenhouse-Gas Assessment Spreadsheet for CAPital Project (GASCAP) tool developed at Rutgers University (2014). The advantage to using pay items is their ability to accurately cover an entire pavement project, including items such as pavement markings, sign posts, etc. When a database of these pay items are created, they can be easily transferred to other projects with modifications where needed. Using a large sample set of mix designs and the flexibility afforded by pay items, this study is able to evaluate general environmental and economic trends and patterns in historical Illinois Tollway mixes and construction activities.

3.4 Analysis Approach

The approach used in this analysis is intended to provide a comprehensive evaluation of the environmental and economic impacts of two types of products (i.e., pavement mixes and construction activities) which are defined by mix designs and pay items. Using this approach, cradle-to-gate processes associated with mix designs include all upstream processes required to produce a mix that is ready for incorporation into a pavement. Cradle-to-placement processes associated with pay items include all upstream processes for the production of materials and mixes required as well as equipment use on-site to complete the defined construction activities.

The cradle-to-gate and cradle-to-placement approaches are a partial implementation of the cradle-to-grave (or LCA) approach defined by ISO14040 and ISO14044. The use, disposal, and maintenance of the products are not considered. The analyses are cut-off at the plant before construction for mixes and on-

site, immediately after construction for the pay items. Figure 3.1 shows the system boundaries of the two products, where each box represents a process that embodies all upstream processes (e.g., raw material production, fuel production, electricity generation, operations, etc.). Using these system boundaries, only the initial environmental and economic impacts are considered; the impact of performance and service life of the materials are considered out of the scope of this work. However, general LCA principles regarding goal and system definition, LCI analysis, impact assessment, and interpretation are still applicable to this study and have been followed where appropriate.

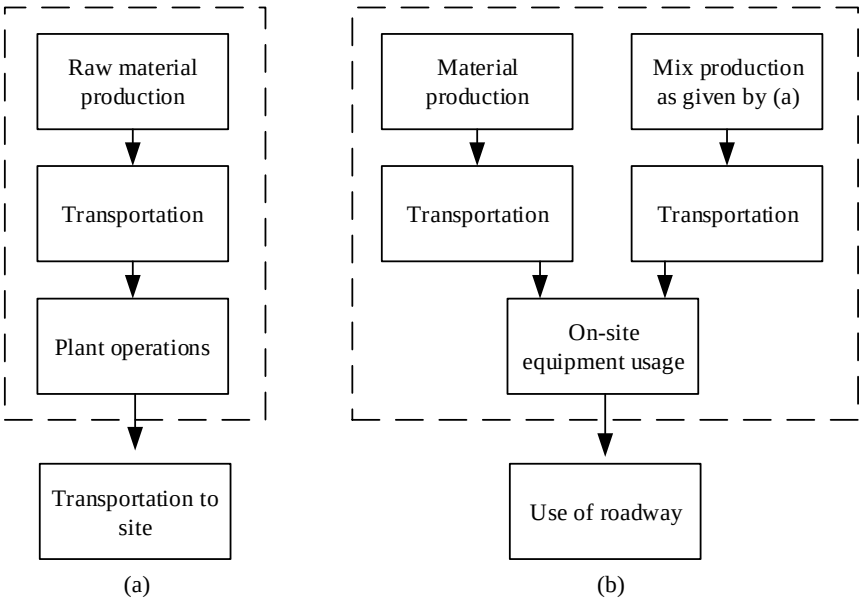


Figure 3.1; System boundaries of the (a) cradle-to-gate approach for mix designs and cradle-to-placement approach for (b) pay items.

3.5 Product Definitions

3.5.1 Mix design definition

In this chapter, the analysis of mix designs refers to a cradle-to-gate assessment of the production of AC and PCC mix designs used in pavement construction. A database of 464 AC mix designs and 461 PCC mix designs was analyzed. These designs represent a portion of those used by the Illinois Tollway in various roadway construction projects from 1998–2014. The mix designs included actual mix parameters (i.e., volumetrics and mix percentages for AC and mass for PCC), material codes, supplier codes, and plant codes. Thus, raw material tonnage could be calculated per cubic yard of each mix. In addition, raw material transportation distances could also be calculated based on supplier and plant codes.

The system boundaries of the mix designs include (1) production of raw material, (2) transportation of raw material to plant, and (3) plant operations. The functional unit was a cubic yard of AC or PCC

suitable for use in an interstate highway. The data quality of the mix designs was very good, considering that actual parameters and transportation were replicated in the analyses. Inadequate mix design records were removed from the analyses (e.g., if AC mix percentages did not add to 100) and transportation assumptions based on typical Illinois values were made when supplier codes were not available (i.e., 20 miles for aggregates, 60 miles for asphalt binder, and 0 miles for RAP, RAS, and mineral filler).

3.5.2 Pay item definition

The analysis of pay items in this paper refers to the cradle-to-placement assessment of construction activities as defined by IDOT and Illinois Tollway regulations for pay items. A set of 140 major pavement-related pay items were analyzed in this study. These pay items were among those that contributed 80% of the cost from each of nine large contracts funded by the Illinois Tollway's Congestion Relief Program (2005–2016).

The system boundaries of the pay items include (1) production of materials and mixes, (2) transportation of materials and mixes to site, and (3) on-site equipment usage. The functional unit varied for each pay item. In order to determine the materials, mixes, and equipment required, the pay items needed to be characterized. Expert judgment as well as IDOT and Illinois Tollway specifications were used to estimate the quantities and types of materials, mixes, and equipment needed for each pay item. The fuel required for each on-site equipment was calculated by estimating the productivity (units/hours) of each pay item activity based on various sources.

3.6 **Environmental Impacts**

In order to evaluate environmental impacts of mix designs and pay items, a database of impacts for each unit process involved in the two products must be compiled. This procedure corresponds to the LCI analysis and impact assessment steps of the ISO LCA methodology. The impact database included four major categories of processes: material production, operations, fuel for equipment, and transportation. Details of the data collection, modeling, and assessment can be found in other related studies (Kang et al., 2014; Kang, 2013; Yang et al., 2016; Al-Qadi et al., 2015; Yang et al., 2015). In general, both primary data from Illinois material producers and secondary data from published sources were collected for material and operations processes. The data were then modeled in a commercial LCA software, SimaPro 8.0.4, to ensure that all upstream impacts were captured using the US-EI 2.2 database (Earth Shift, 2013). For fuel and transportation, the U.S. EPA programs NONROAD2008 and MOVES2010 were used to generate emissions for the Illinois region related to fuel combustion in different construction equipment and hauling trucks, respectively. The impacts related to the production of fuel for these off and on-road vehicles were taken from US-EI 2.2.

Major assumptions and limitations exist in terms of relating unit processes to the products. For mix designs, aggregates were only differentiated as crushed or natural and not by gradation. Asphalt binder types were distinguished between ground tire rubber-modified, polymer-modified, and straight binder. Recycled materials and by-products (i.e., RAP, RAS, SCMs, and mineral filler) were analyzed using a cut-off allocation method. This means only processes related to the production of the secondary material are considered (e.g., crushing of RAP, shredding of RAS, drying of fly ash) and processes related to the production of the primary material (i.e., asphalt pavement, iron, and coal) are not considered. In addition, AC and WMA were analyzed using separate plant unit processes that reflected the reduction in energy needed for lower mix temperatures (Yang et al., 2014); the production and transportation of WMA additives were not included due to lack of data. Similarly, the production and transportation of PCC admixtures were not considered. For pay items, the estimated horsepower and type of equipment specified in their characterization were matched as closely as possible to the unit processes available from EPA's NONROAD2008.

According to ISO14044, environmental impacts for each unit process must then be assessed from the LCI (e.g. emissions, raw resources used) based on an established and appropriate characterization method. EPA's TRACI 2.1 is widely used in North America and is used to calculate GWP for unit processes in this study. In addition, total cumulative energy is also reported in the analysis from SimaPro, which encompasses all upstream and downstream primary energy consumption. The energy considered in this analysis only includes energy from fuel consumption, not energy stored in material form (e.g., feedstock energy), which is found in materials such as asphalt binder.

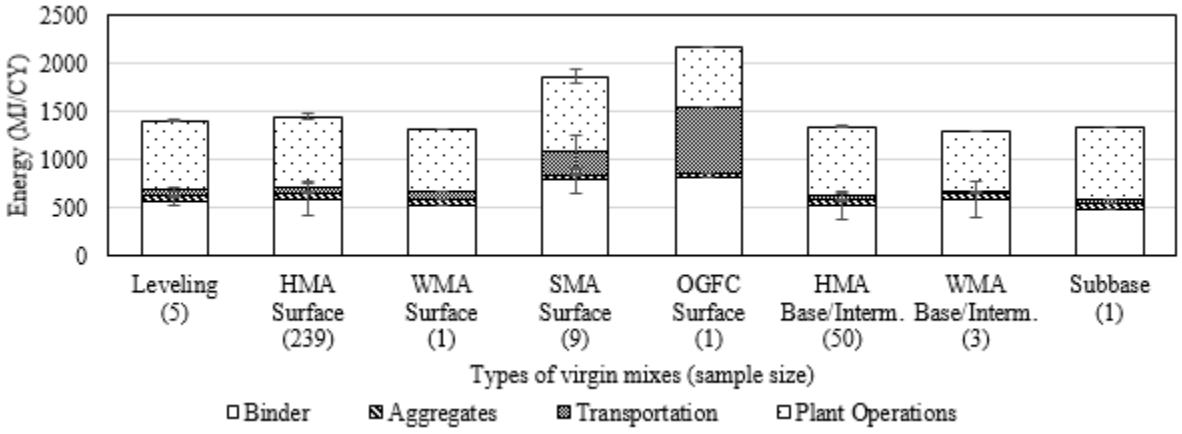
3.7 Economic Costs

The economic costs of the mix designs and pay items were obtained using separate methods. Unit costs for each material in the mix design were considered to determine a total mix cost using a bottom-up approach, while the unit cost of the entire pay item was used. Material costs were estimated based on typical Illinois prices. The costs of recycled materials were obtained from a 2013 IDOT report (Lippert et al., 2014), while costs for aggregates, asphalt and cement binder, and transportation were estimated based on an online appraisal of producer prices and reports as well as expert opinion (David Lippert, personal communication, March 10-12, 2015; Statistica, 2015). For example, asphalt binder was estimated to have a freight on board (FOB) cost of $500/ton, modified binder $575/ton, and Portland cement $86/ton, while aggregate prices were between $13–18/ton. Pay item costs were determined using average costs from bid tabulations of the same nine Illinois Tollway contracts used to select the pay items.

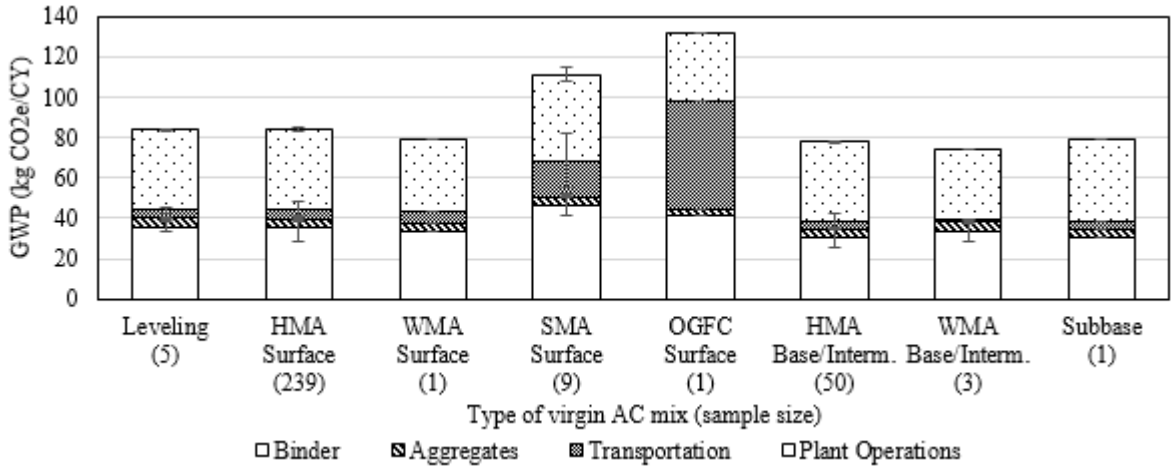
3.8 Environmental Analysis

3.8.1 Environmental analysis of mix designs

To better analyze the environmental burdens of historical Illinois Tollway mix designs, AC and PCC mixes were grouped into various subcategories. Eight subcategories were considered for the AC mixes, including leveling course, HMA (dense-graded) surface course, WMA surface course, stone mastic asphalt (SMA) surface, open-graded friction surface course (OGFC surface), HMA (dense-graded) base/intermediate course, WMA base/intermediate course, and subbase. Many of these subcategories contain mixes with and without recycled materials (i.e., RAP and RAS). To avoid compounding variables, only virgin mixes without recycled materials for each subcategory were first analyzed; the energy and GWP for major processes are shown in Figure 3.2 with error bars indicating one standard deviation.



(a)

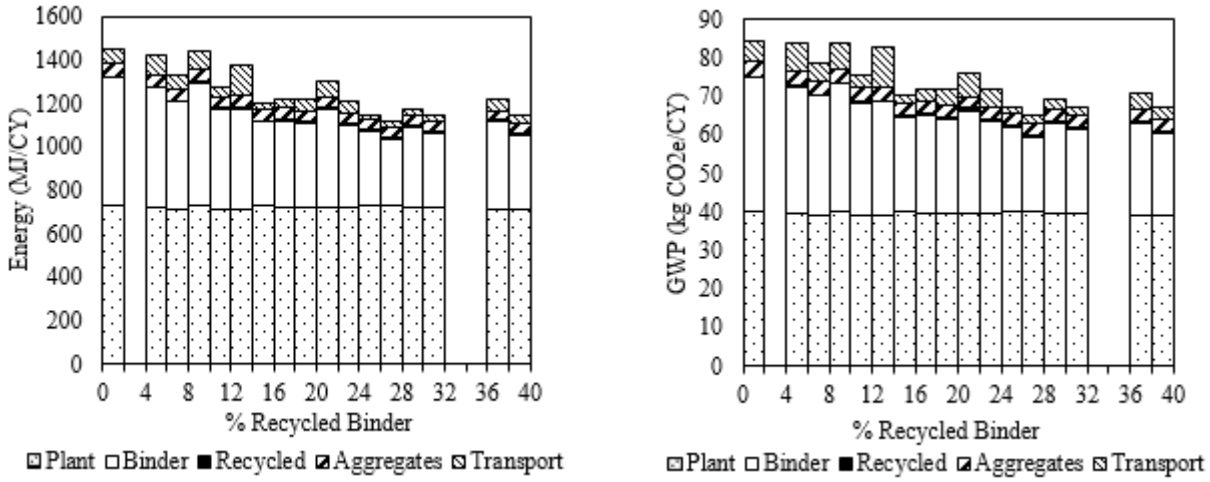


(b)

Figure 3.2: Analysis of (a) energy and (b) GWP for various types of AC mixes without recycled materials.

Overall, the process with the largest standard deviation is transportation. Most raw materials are obtained from nearby sites when available. On average for the Illinois Tollway, asphalt binder is transported 53 miles to plant, aggregates 30 miles, and recycled materials 4 miles; however, higher quality aggregates for SMA and OGFC mix are often transported from Wisconsin to Illinois for an average of 113 miles. This situation is accurate in Illinois, but may vary in other regions. The high transportation burden along with the use of modified binders for SMA and OGFC contribute to the more severe environmental impact of these mixes. Modified binders include ground tire rubber-modified binders and polymer-modified binders whose incorporation of additives and extra processing result in higher environmental burdens. However, along with the more costly acquisition of these higher quality materials is the expectation of a more durable, longer lasting pavement. The potential environmental savings from improved pavement performance is out of this study scope; which only considers initial costs and environmental impacts; a full life-cycle approach would address this issue.

The results in Figure 3.2 exclude mixes with recycled content, which is another influential variable that can be investigated. RAP and RAS are both recycled materials requiring less effort to produce than virgin binder and aggregate, the raw materials they can partially replace. In addition, plants often have stockpiles of RAP and RAS on-site, reducing the need to transport more materials. Figure 3.3 shows the trend between increasing recycled binder content (i.e., greater amounts of RAP and RAS) and decreasing environmental impacts for 107 surface mixes.



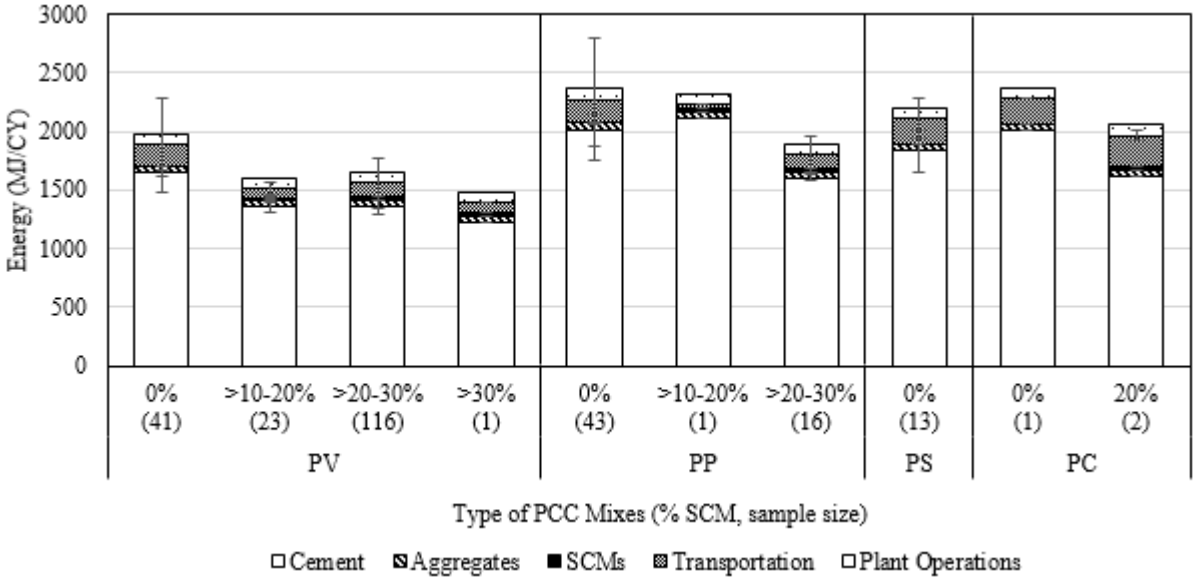
(a) (b)

Figure 3.3: Effect of recycled binder content on (a) energy and (b) GWP for surface AC mixes.

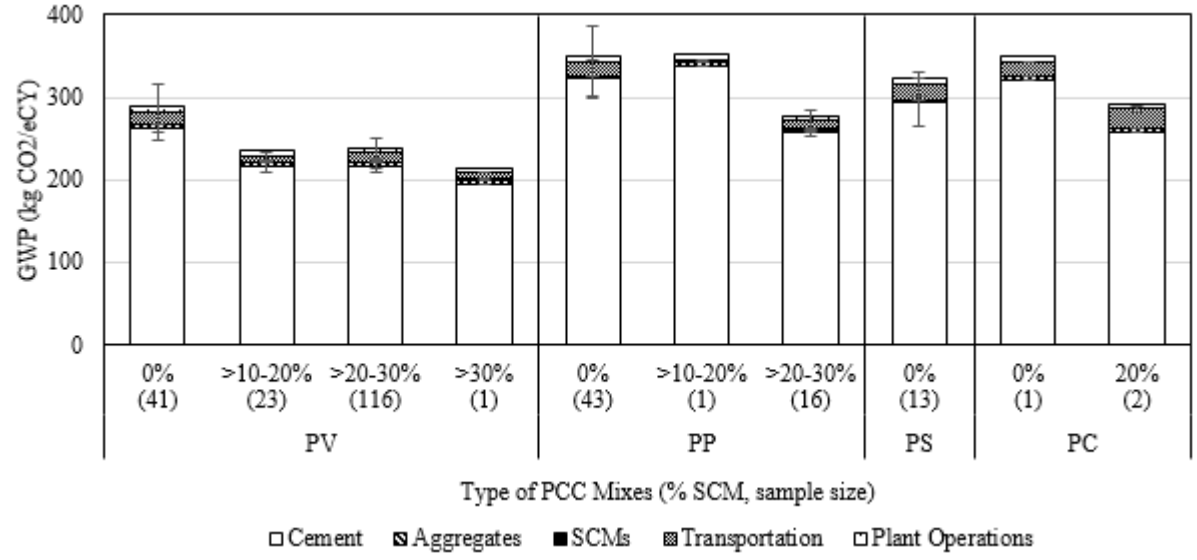
Only surface mixes are included to avoid compounded effects due to mix type. Inconsistencies in the trends shown in Figure 3.3 are due to high variability in transportation as well as the use of modified binders.

Therefore, longer hauling distances and the use of non-conventional binders may substantially reduce initial environmental benefits gained from using recycled materials.

The PCC mixes were also divided into subcategories depending on their class: pavement (PV), pavement patching (PP), prestressed precast (PS), and precast (PC). In addition, these mixes had differing amounts of SCM replacement of virgin cement. Thus, the environmental analysis in Figure 3.4 shows corresponding energy and GWP for various classes of mixes as well as differing SCM contents.



(a)



(b)

Figure 3.4: Analysis of (a) energy and (b) GWP for various types of PCC mixes with and without SCM.

Similarly to that for the AC mixes, transportation is also an inconsistent variable among the historical mixes. In addition, the PCC classes have different amounts of cement, which is a major cause of variation among the mix types. Based on the mixes analyzed, PV mixes have an average cement content of 494 pounds per cubic yard (lb/yd^3), PP 663 lb/yd^3, PS 638 lb/yd^3, and PC 607 lb/yd^3. The amount of cement drives the value of the environmental impact because its contribution to energy and GWP in Figure 3.4 is 78–91% and 88–96%, respectively, of the entire mix.

The effect of increasing amounts of SCM can also be seen in Figure 3.4. The SCM levels are binned as 0%, >10–20%, >20–30%, >30%, and 20% of the total cementitious content, and no mixes were found to have between >0–10% SCM. A clear decreasing trend in environmental impacts can be seen for the PV and PC mixes with increasing SCM. The environmental impacts of the PP mixes decrease from 0% to >20–30%, but the sole >10–20% mix does not follow this trend due to its exceptionally high total cementitious value of 880 lb/yd^3. Thus, the large sample size of historical AC and PCC mixes provides general trends and ranges in environmental impacts of various mixes; however, the exact context of these mixes is unknown and thus some mixes may have required special materials or designs that cannot be accounted for in this analysis.

3.8.2 Environmental analysis of pay items

For pay items, the environmental trends are more difficult to analyze on a one-to-one basis due to differences in functional unit of the products. Thus, in order to evaluate the pay items in context, one full-depth AC pavement (FDAC) and one composite PCC pavement (PCCP) reconstruction Tollway project were chosen for analysis. Each project had over 350 pay items, so pavement items contributing to the top 80% of the cost were chosen for evaluation. The selected pay items for the reconstruction projects are shown in Figure 3.5 along with their environmental impacts. The pay items in the figure are not directly comparable due to differences in function and unit, but the results give a general indication of the environmental impacts of different types of construction activities.

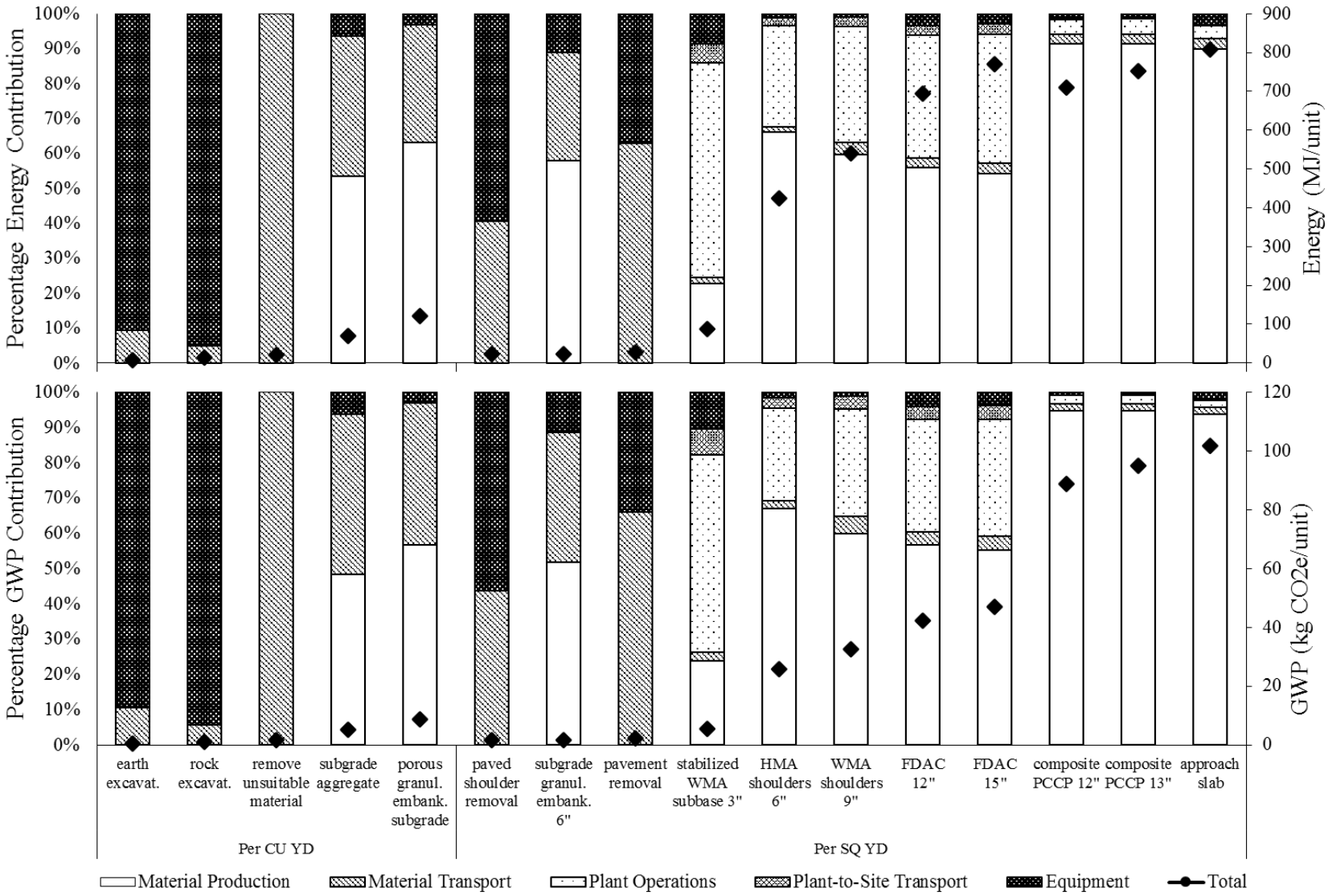


Figure 3.5: Percentage contributions for (top) energy and (bottom) GWP of each major pay item.

The results in Figure 3.5 show a breakdown of the contributions of major types of unit processes in the pay items (i.e., material production, material transportation, plant operations, to/from-site transportation, and equipment usage). The percentage contributions for these categories vary widely depending on the type of construction activity, though the magnitude of energy and GWP contributions are similar within each pay item. In addition, the total energy and GWP impacts within each pay item have corresponding trends. The exception to this trend is the pay items containing Portland cement (i.e., PCCP and approach slab), which releases a large amount of CO_2 from calcination during production. The pay item for approach slab construction has the greatest environmental impacts per square yard due to the high intensity material production needed for 12 inches of PCC and steel reinforcement. In general, the pay items with the highest environmental impacts tend to be related to the construction of the upper pavement layers (i.e., FDAC, PCCP), followed by paved shoulders, subbase and subgrade, and lastly excavation and preparation.

3.9 Relationship between Cost and Environmental Impacts

3.9.1 Cost and environmental impact in mix designs

Energy and GWP often correlated to fuel usage, so it is expected that environmental impacts are also closely related to costs. The cost-impact relationships considering all types of AC and PCC mixes in Figure 3.6 show an increase in energy and GWP with an increase in costs. The correlation between cost and environmental impacts is more uniform in the AC mixes, with GWP being more strongly correlated to cost than energy. The separated group slightly above the trendline in Figure 3.6(a) correlates to the mixes with modified binders. This implies that the initial environmental impact value associated with modified binders is relatively higher than the corresponding initial economic cost in this study.

The graphs in Figure 3.6(c, d) show stratification of the data based roughly on mix class and more precisely on cement content. While the cement contributes approximately 80–90% of the environmental impacts of the mix, its contribution to the cost of the mix is 20–50%. Therefore, higher amounts of cement result in a relatively higher environmental impact than economic cost for the PCC mixes in this study. In other words, similar to the modified binder in the AC mixes, the initial economic value assigned to cement is relatively lower than the initial environmental burden assigned to cement.

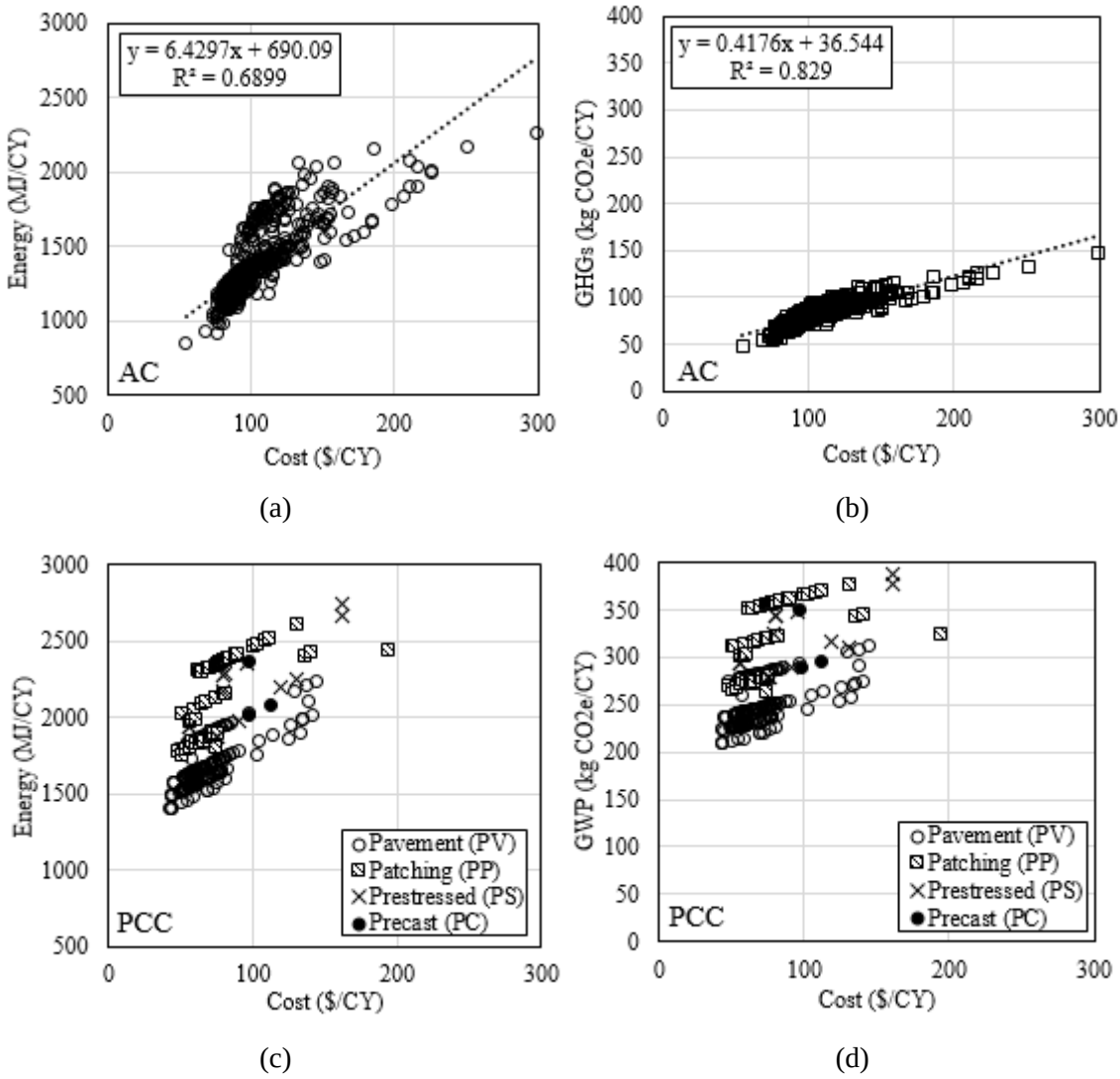


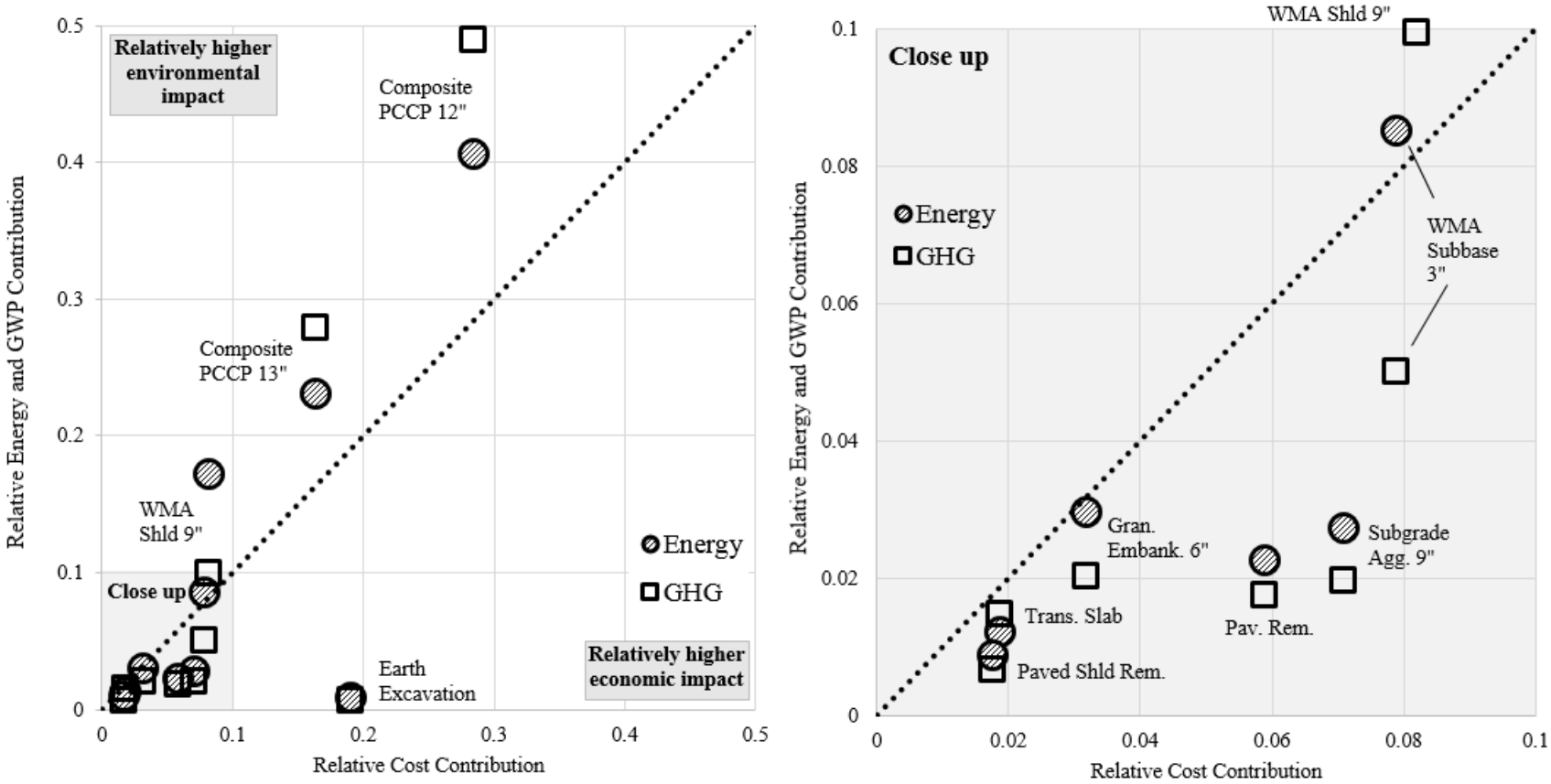
Figure 3.6: Relationships for AC mixes between (a) total cost versus energy and (b) total cost versus GWP and for PCC mixes between (c) total cost versus energy and (d) total cost versus GWP.

3.9.2 Cost and environmental impact in pay items

The major pay items selected must again be considered in the context of a project in order to evaluate the relationship between cost and environmental impact. Considering solely the subset of pavement pay items from the two reconstruction projects described previously, the relative cost and environmental contributions of the pavement pay items are determined from the actual project quantities of the pay items. Thus, the y-axis in Figure 3.7 represents a pay item's percentage environmental contribution out of the total environmental impacts from the pavement items in the project and similarly for the economic contribution. By using actual project quantities, discrepancies from comparing pay items with different units and functions are circumvented. Figure 3.7 shows a relatively linear trend among the pay items for each project,

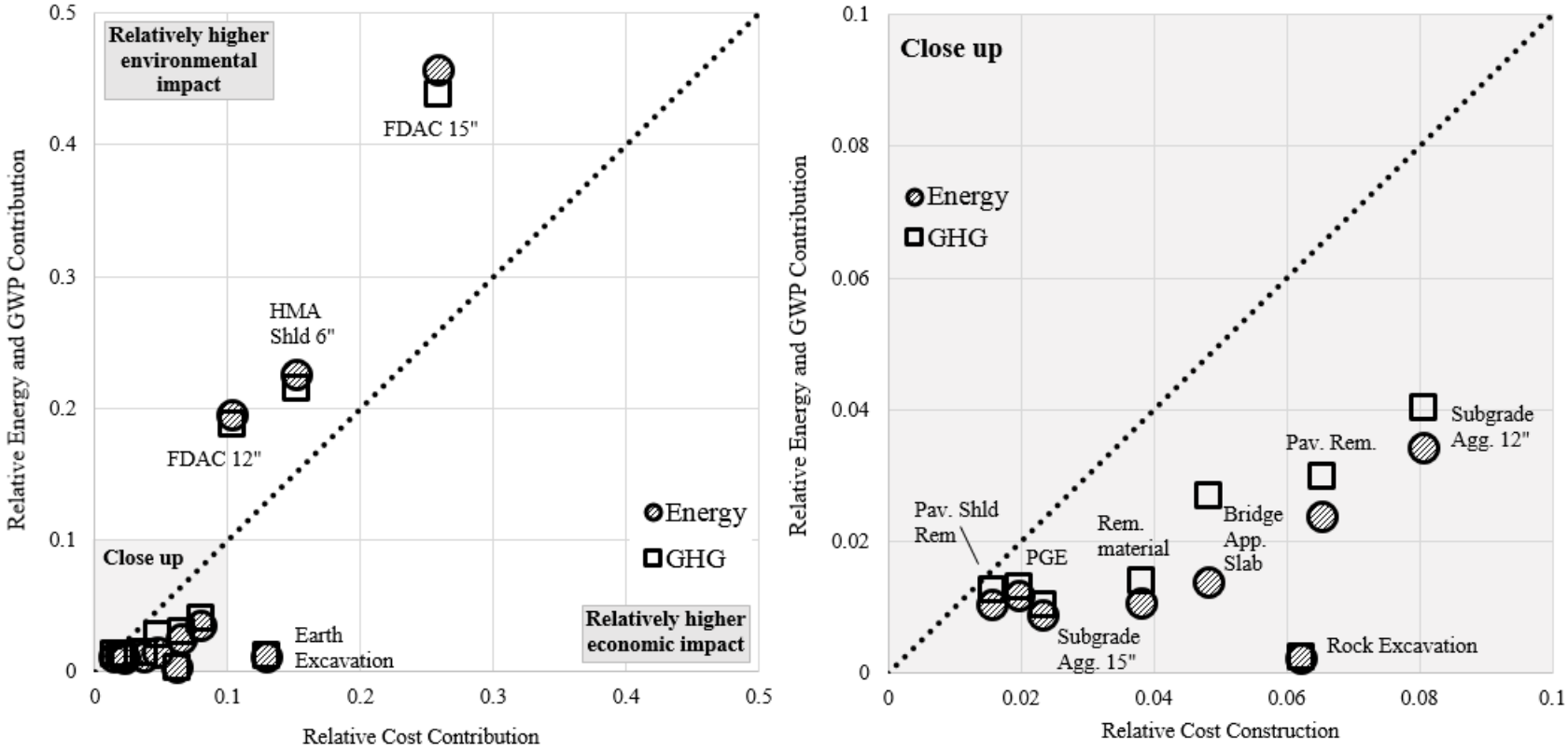
implying that economic and environmental costs of construction activities are positively correlated as expected.

Thus, the equality lines on each subfigure represent the locations where environmental impacts and economic costs have the same relative contribution to the project. It can be seen from Figure 3.7 that the pay items contributing the highest costs tend to have a relatively higher environmental impact (being above the equality line), while those that have lower costs tend to have a relatively lower environmental impact (being below the equality line). Interestingly, excavation has a substantially lower environmental impact contribution with <2% of the total pavement impacts compared with 13-20% of the total pavement costs, implying that further improvement in environmental sustainability for this item may be difficult. Excavation does not require any material production and minimal material transportation, as 87–88% of its environmental burdens comes from equipment usage.



(a) (b)

Figure 3.7: Relative contributions of each major pay item to the total cost and environmental impacts in the (a) (b, close up) PCCP and (c) (d, close up) FDAC reconstruction projects.



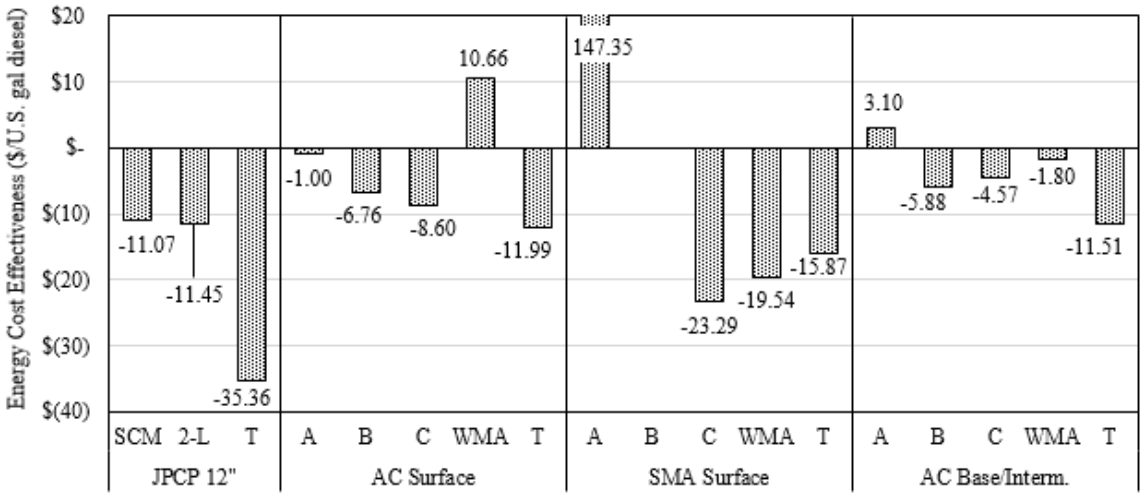
(b) (c)

Figure 3.7 (cont.): Relative contributions of each major pay item to the total cost and environmental impacts in the (a) (b, close up) PCCP and (c) (d, close up) FDAC reconstruction projects.

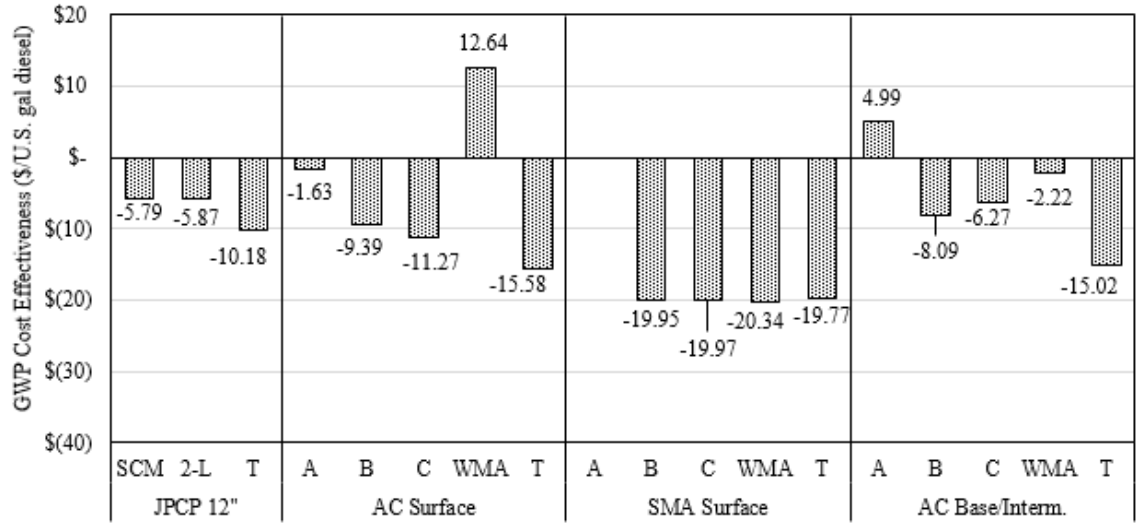
3.10 Cost Effectiveness Analysis

As the highest contributing items in a construction project are often related to the upper pavement layers, this study will focus on the effect of sustainable strategies related to these pay items. Sustainable strategies include those related to mix designs and mix technologies (e.g., use of recycled materials, SCMs, WMA) and those focusing on construction practices (e.g., two-lift concrete pavement, shorter plant-to-site hauling distances). Each of these strategies correlate with a different cost, which may be greater or lower than the original design. Thus, the GWP and energy cost effectiveness (CE) can be calculated in terms of cost-per-unit-energy or cost-per-unit-GWP (Lutsey and Sperling, 2009).

The results presented in Figure 3.8 show the average initial CE of various sustainable strategies as applied to alternative mix designs for an equivalent one square yard of jointed plain concrete pavement (JPCP) or one ton of AC surface, SMA surface, and AC base/intermediate course. The reference mixes include average plant-to-site hauling distances as well as 0% recycled material and traditional hot-mix technology for asphalt items, traditional JPCP and 0% SCM for the PCC item. As one unit megajoule (MJ) and one unit of kilograms per carbon dioxide equivalence (kg CO_2e) is difficult to contextualize, the costs are normalized by the energy and GWP from producing and combusting one U.S. gal of diesel in a vehicle. The analysis assumes that the stakeholder is evaluating the cost of implementing various strategies in order to reduce a certain amount of environmental impacts. Thus, the CE represents the price paid (positive CE) or the amount saved (negative CE) from implementing the respective strategy in order to reduce the amount of GWP or energy equivalent to that from one gal of diesel. In the latter case, cost savings occur alongside environmental savings. It should be emphasized that these CE values are averages based on the sample of mixes analyzed – the values can change significantly for individual mixes or projects. In addition, the costs are for the entire pay item and also reflect variables unrelated to materials and equipment, such as labor. Per the scope of the paper, the costs and impacts reflect initial savings or burdens, and the life-cycle CE may vary depending on future performance or service life.



(a)



(b)

Figure 3.8: Average initial cost effectiveness value for (a) energy and (b) GWP for various sustainability strategies, where "SCM" represents >10–20% SCM; "A", "B", and "C" represents 0–20%, 20–30%, and >30% recycled binder, respectively; "2-L" represents two-lift concrete pavements; and "T" represents a 20% decrease in plant-to-site transportation.

For the PCC mixes, a CE is estimated for implementing the use of >10–20% SCM, two-lift composite pavement, and decreased plant-to-site transportation. A decrease in transportation has the greatest CE because it directly reduces the amount of environmental impacts with relatively more cost savings for a mix. On the other hand, the use of SCM reduces a greater amount of impacts (especially GWP) per square yard, but the average cost is relatively higher, possibly due to additional handling and transportation of SCM materials.

The AC mixes have on average both initial cost and environmental savings for most strategies except WMA for AC surface courses and low levels of recycled binder (A) for AC base/intermediate and SMA surface courses. As seen in Figure 3.3, increasing recycled binder content may not always result in lower initial environmental impacts due to other variables such as hauling distances and type of binder used, particularly when used in lower amounts. For example, average GWP savings were not evident in the data set for "SMA Surface, A" and the average energy savings were very small. Coupled with a higher cost for these mixes, the CE for energy savings becomes extremely expensive ($147.35). The use of WMA in AC surface and base/intermediate courses have less desirable CE due to its higher costs; however, as SMA already has a relatively higher cost than the reference, the extra cost due to WMA is not as prohibitive. Finally, only GWP and not energy savings benefits were found for "SMA surface, B", implying that the magnitude and even direction (i.e. positive or negative) of the CE depends on the environmental impact considered.

In general, the majority of the sustainable strategies analyzed in this study have both initial cost and environmental impact savings. The average CE of these strategies range from -$1.00 to -$35.36 for energy and -$1.63 to -$20.34 for GWP. On the other hand, strategies required additional cost to procure savings have CE values ranging between +$4.99 to +$12.64 for GWP and +$3.10 to +$147.35 for energy. For comparison, the average U.S. Midwest price of diesel in 2012 was $3.90 per gal (EIA, 2015), suggesting that strategies with positive CE values significantly above this value may not be sustainable without superior service life or performance.

3.11 Summary

The purpose of the study in this chapter was to evaluate sustainable strategies in pavement construction with respect to both environmental and economic impacts. A large database of pavement mix designs and pay items were obtained from historical Illinois Tollway projects and systematically analyzed based on materials, amounts, transportation distances, specifications, and costs. Environmental impacts of the mix designs and pay items were calculated using a LCI database developed to represent Illinois production and construction processes while economic costs were estimated based on Illinois material prices and bid item tabulations. The analysis presented was divided into three parts, each with key findings.

- First, while increased use of common sustainable materials and technologies (i.e., SCMs, RAP, RAS, and WMA) showed a general reduction in environmental impacts among the mix designs, long hauling distances and modified binders could potentially reduce environmental benefits.
- Second, a positive correlation between cost and environmental impacts was found for pay items, with higher cost and environmental impacts linked to activities related to upper pavement layers,

increasingly lower costs and impacts for lower pavement structures, and the lowest burdens ultimately for preparation activities.

- Third, the majority of common sustainable strategies evaluated had on average both initial cost and environmental savings while a minority required additional costs to implement environmental savings, indicating that many sustainability strategies may be implemented without economic detriment assuming equal or better service life.

Overall, this study used a systematic approach to analyze a large sample of actual mix designs and pay items, showing general trends, inconsistencies, and implications of the environmental and economic impacts of commonly accepted sustainable strategies in pavement construction.

CHAPTER 4

IMPLEMENTING PAVEMENT LIFE-CYCLE ASSESSMENT FOR AGENCIES AS A SOFTWARE[6]

4.1 Motivation

The work leading up to this chapter include the development of regional LCI databases as well as partial cradle-to-gate and cradle-to-ground environmental impact analyses of pavement mixes and pay items, respectively. Thus, the next step in this dissertation is to incorporate and expand the work from the previous chapters into a full LCA framework and implementation. There has yet to be a pavement LCA software that any transportation agency in the U.S. has embraced and implemented in their programs. This gap is due to policy complications as well as technical limitations related to lack of relevant LCI data, lack of an appropriate tool to perform LCA, and lack of experience in interpreting LCA results.

This chapter describes a full LCA software (rrLCA 1.0) that was designed and implemented based on five years of collaboration with the Illinois Tollway and its consultants. As such, the software is intended to be directly applicable to transportation agencies, fitting into their procurement and acquisition processes through the use of pay (or bid) items. In addition, the framework for the software includes all life-cycle stages (i.e., material production, construction, maintenance and rehabilitation, use, and EOL) as well as multiple roadway/roadside components (i.e., drainage, landscape, lighting, pavement, and structures) that are not typically considered in other LCA software. A series of pavement case studies are also analyzed, with results presented in different perspectives that may be useful to agencies. By taking into consideration the needs of an agency with respect to appropriate LCI data, user inputs, design relevance, and interpretation considerations, an LCA software can be more successfully implemented and utilized by transportation agencies wishing to evaluate the environmental impacts of their major construction acquisitions.

[6] Part of the work in this chapter was presented in poster form as "Development and application of a roadway/roadside life-cycle assessment software for the Illinois Tollway" at the *96th Annual Meeting of the Transportation Research Board* (January 8-12, 2017). The authors of this work include Rebekah Yang, Wonjae Yoo, Hasan Ozer, and Imad Al-Qadi. Any figures, tables or data not created by the author of this dissertation is indicated within the chapter.

4.2 Background

More and more interest in sustainability over the last decades has prompted transportation agencies to take tangible steps toward reporting and reconsidering their economic, environmental, and social footprints. Recently, as evidenced by the FHWA's reference document "Towards Sustainable Pavement Systems" (Van Dam et al., 2015), this mentality has come to the forefront of the road infrastructure industry. However, in order to make progress toward a sustainable infrastructure, agencies must have a way to systematically assess their past, present, and future economic, environmental, and social impacts.

Traditionally, LCA studies for roads are largely focused on the pavement of a roadway/roadside system. The first road LCA studies emerged in the 1990s – 2000s predominantly from Europe (Häkkinen & Mäkelä, 1996; Stripple, 2001). These studies largely focused on the development of inventory data or emissions from various processes (i.e., production of asphalt binder, generation of electricity) for pavement as well as lighting. In the 2010s, interest moved towards developing models related to the use-phase of the pavement, which includes elements such as rolling resistance, albedo, carbonation, and leaching (e.g., Wang et al., 2012; Yu & Lu, 2012). In the last two decades, various tools were developed to better implement the LCA methodology for roads. Some tools were developed as generic road LCA software, while others were developed to analyze specific topics related to pavement.

The earliest generic road LCA tool, PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects), was released in 2004 in the U.S. with an update in 2011 (Horvath, 2003a, 2003b). PaLATE is implemented on an Excel spreadsheet to calculate impacts from material production and construction from pavement only, using mostly economic input-output inventory data. Another tool, GASCAP was developed in 2011 in an Excel spreadsheet for the New Jersey Department of Transportation (Noland & Hanson, 2011). This model captured a larger scope of the road to evaluate material and construction processes related to various roadway/roadside elements. In addition, impacts from work zones and lighting usage were also included. Finally, the PE-2 (Project Emission Estimator) was released shortly following as a web application based on information from Michigan Department of Transportation (Mukherjee & Cass, 2012). This application includes a separate "material estimator" to evaluate impacts from producing various roadway/roadside elements, an "equipment estimator" to evaluate impacts from various equipment, and an "LCA estimator" to evaluate the material production and construction (including emissions from work zones) from specific maintenance, rehabilitation, and reconstruction activities relevant to the sponsoring agency.

Related LCA tools have also been developed outside of the U.S. Notable are DuboCalc, Athena Pavement LCA Tool (formerly Athena Impact Estimator for Highways), and ECORCE. Developed in 2010, DuboCalc is maintained by the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat)

(Van Geldermalsen, 2013). It is a software that monetizes the environmental impacts of material production and construction for general civil engineering infrastructure using LCA, ultimately outputting an environmental cost indicator that has been integrated into the Dutch procurement process. The data used in this tool is part of a national database that is used in both buildings and other civil engineering applications and makes use of industry and product specific Environmental Product Declarations (EPD). Athena Pavement LCA software was developed by the Athena Sustainable Materials Institute in Canada alongside their Impact Estimator for Buildings (2015). The software is freely available and has since been implemented online as a web application. It contains a large, accessible database of materials and equipment information, and also includes models to evaluate the pavement use-phase. Finally, ECORCE (ECO-comparator applied to Road Construction and Maintenance) v2.0 was released in 2013 by Ifsttar (French Institute of Science and Technology for Transport, Spatial Planning, Development and Networks) (Jullien et al., 2015) to evaluate material production and construction. The data used in ECORCE represent the French context and are also available on a large public database.

In addition to the generic software developed, a number of specialized software tools have also been created. In 2005, a Danish software called ROAD-RES was released as an environmental management decision tool specifically focusing on evaluating the impacts of landfilling bottom ash from municipal solid waste incineration or recycling the material for use in road construction (Birgisdóttir, 2005). This private, standalone software features inventory data from Danish producers and contractors as well as from a Swedish study (Stripple, 2001). In 2009, an unnamed software tool from the United Kingdom was developed as a series of Excel spreadsheets (Huang et al.). This private software was developed specifically to look at the effect of recycling and rehabilitation of asphalt pavements by considering the material production and construction stages. Finally, in 2010, asPECT (asphalt Pavement Embodied Carbon Tool) was developed in the United Kingdom specifically for assessing the greenhouse gases of asphalt mixtures from cradle to site (Wayman et al., 2011).

The aforementioned tools all consider the material production and construction stages of the life cycle. A number of them include the maintenance (i.e., PaLATE, PE-2, GASCAP, Athena, ECORCE, DuboCalc, asPECT) and EOL (i.e., PaLATE, GASCAP, asPECT) stages; however, only a few include the use-phase (i.e., PE-2, GASCAP, Athena). Thus, only two of the software reviewed above, GASCAP and Athena, consider the entire life cycle of the system. In addition, only GASCAP and PE-2 makes provisions to include the material production and construction of other elements of the roadway/roadside, but the bulk of the inventory data included in these software are largely from economic input-output information rather than region-specific data collection. Finally, the software that include the initial life-cycle stages of other elements beyond pavement do not also fully consider the corresponding maintenance, use, and EOL of

these roadway/roadside elements (e.g., lighting element usage may be considered but not storm water runoff impacts from drainage elements or mowing from landscaping elements).

While there are various pavement LCA tools available, there still lacks a comprehensive LCA tool that considers a complete set of roadway/roadside elements through all life-cycle stages. In addition, there are shortcomings not yet overcome that prevent an existing software to include a regionalized inventory database as well as all applicable life-cycle stages and multiple roadway/roadside elements.

4.3 Objective

The aim of the work presented in this chapter is to develop a complete LCA software that can be directly and appropriately implementable by a transportation agency. In order to do so, the software must consider all life-cycle stages (i.e., material production, construction, maintenance and rehabilitation, use, and EOL) as well as have the ability to consider all major roadway/roadside elements relevant in construction contracts (i.e., drainage, landscape, lighting, pavement and structures). In addition, a series of pavement case studies will be analyzed using the software to demonstrate how an agency may utilize such an LCA tool.

4.4 Goal and Scope

This LCA work was carried out in accordance with the ISO14040 series (2006a, 2006b) and based on guidelines given by the pavement LCA framework developed by FHWA (Harvey et al., 2016).

The Roadway/Roadside LCA software version 1.0 (rrLCA 1.0) developed through this work was customized for the needs of the Illinois Tollway, which intends to use the tool to assess the environmental impacts of their construction projects. Specifically, the agency is interested in self-evaluating the progress in sustainability of discrete projects over time as well as in identifying areas where changes in policy can result in greater benefits to the environment. Therefore, the features in rrLCA 1.0 are specific to Illinois Tollway and efforts have been made to ensure that the data is as representative as possible to the Northern Illinois context.

The scope of the LCA includes all roadway/roadside elements of a road system. The product system of the LCA includes five modules: drainage, landscape, lighting, pavement, and structures. The system adheres to the structural and functional requirements as mandated by IDOT and Illinois Tollway specifications. The geography of the LCA is limited to the region in Northern Illinois that encompasses the tollway's network. A schematic of the system boundaries including the entire life-cycle of the roadway/roadside system is given in Figure 4.1. All processes except those identified as module-specific components (e.g. in the use-phase stage) are relevant to all modules.

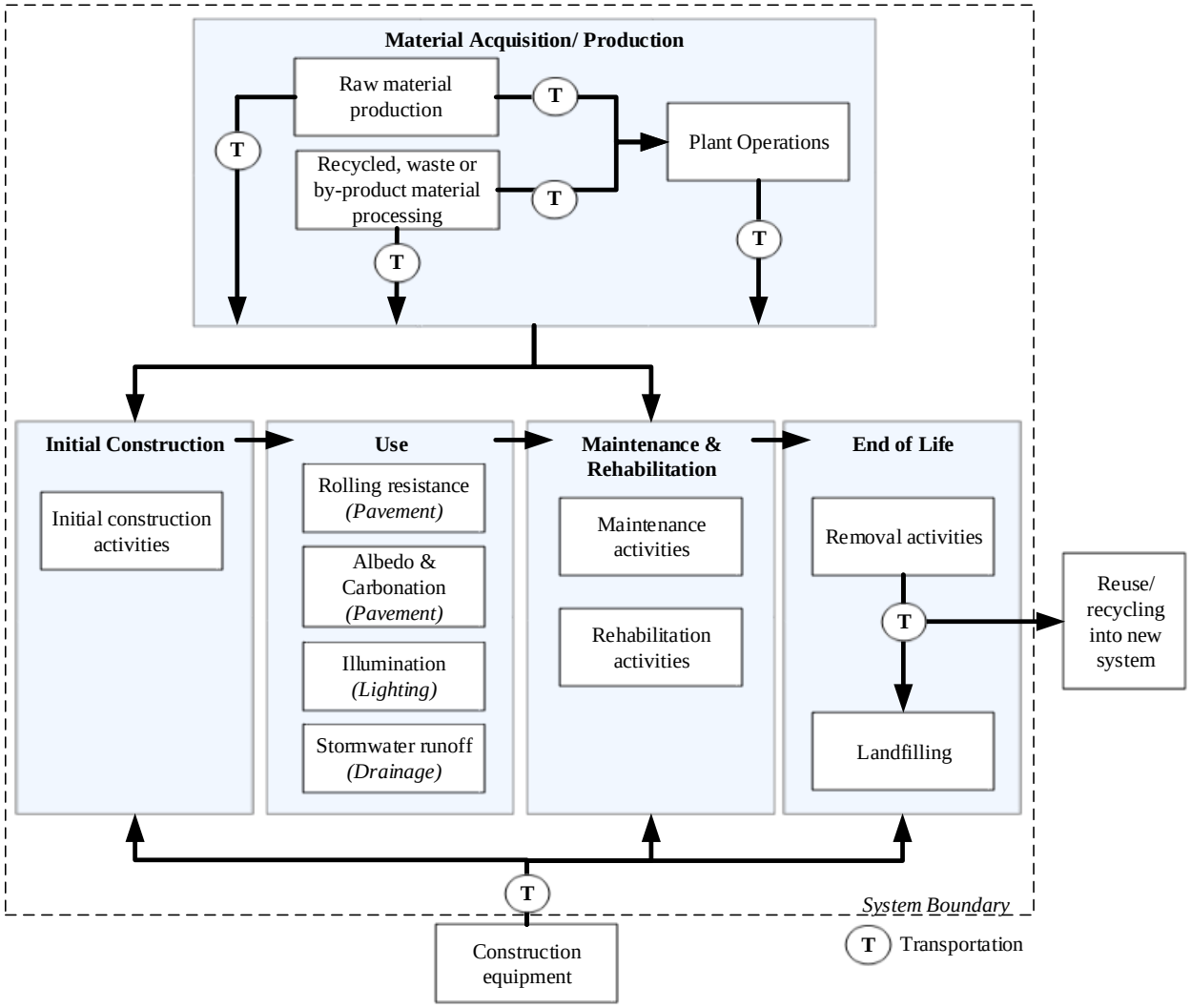


Figure 4.1: Overall system boundaries of the roadway/roadside LCA.[7]

Each module has its own functional unit due to differences in analysis period and functionality that arise among the five modules. For example, the functional unit for the drainage and lighting modules is lane-mile-year and for the landscape module it is square-foot-year. The various components (i.e., overhead signs, retaining and noise walls, median barriers, overhead signs, bridges) within the structures module have a functional unit of either square-foot-year or linear-foot-year. The functional unit for the pavement module takes into consideration the vehicles traveling along the roadway and is per vehicle-mile-traveled (VMT); this choice of functional unit is discussed elsewhere (Ziyadi et al., 2017). A summary of the

[7] The drainage-specific components were developed by Diana Byrne, while the landscape, lighting, and structures-specific components were developed by Applied Research Associates, Inc. The pavement components for traffic and the use-phase were developed by Laura Ghosh and Mojtaba Ziyadi.

functional units and their derivations are listed in Table 4.1, where S is the set of all life-cycle stages s, E_s is the environmental impact for stage s, L is the length of the project or component, W is the length of the project or component, N is the number of lanes, and Y is the analysis period in years.

Table 4.1 Functional Unit Calculations for Each Module

Modules	Functional Unit Calculation	Units
Drainage, Lighting	$\frac{1}{N \times L \times Y} \sum_{s=1}^{S} E_s$	Per lane-mile-year
Landscape, Structure: Noise Wall, Structure: Retaining Wall Structure: Bridge	$\frac{1}{W \times L \times Y} \sum_{s=1}^{S} E_s$	Per square-foot-year
Structure: Culvert, Structure: Median Barrier, Structure: Overhead Sign	$\frac{1}{L \times Y} \sum_{s=1}^{S} E_s$	Per linear-foot-year
Pavement	$\frac{10^6}{VMT} \sum_{s=1}^{S} E_s$	Per million VMT

There are two major allocation rules that have been applied to the LCA. First, for materials considered to be recycled products or co-products, a cut-off rule is applied. Thus, only processes directly related to post-processing or preparation of the products are attributed to the secondary materials, and processes required to produce the original material remain with the primary material. For example, fly ash is considered a co-product of coal production, so only processes related to the drying, storage, and handling of material upon being released from the coal production facility is considered. Second, a consistent cut-off allocation rule is also used for the EOL stage. The boundary between the current and future pavement systems is drawn after dismantling/demolition and handling of the remaining material on the job site and before the processing of any material destined to be recycled or reused. Furthermore, for any remaining material on the job site destined to be disposed of, the impacts of landfilling are considered in the current pavement system. Using this allocation rule, the benefits of recycling are given to the system using, rather than producing, the recycled material. The implications of using these allocation choices are further studied in Chapter 5.

Finally, the cut-off criteria for the LCA study is based on economic cost of the pay items included in the project. There are hundreds of pay items included in each roadway project, making it impractical to meticulously define all of the materials, equipment, and other characteristics for each item. An economic cut-off criterion is used where the pay items included in the analysis must satisfy at least one of the following criteria: (1) contribute to the top 95% (pavement, structures) or 90% (drainage, landscape, lighting) of the total economic project cost for each module's set of pay items, or (2) contribute a minimum

of 0.5% (pavement, structures) or 1.0% (drainage, landscape, lighting) of the total economic project cost of each module's set of pay items. The effect of using the chosen cut-off criteria is evaluated in Chapter 5.

4.5 Software Architecture

The LCA tool is implemented in a series of Microsoft Excel workbooks and add-ins. Extensive use of Visual Basic for Applications (VBA) allows the user to navigate through the spreadsheets and graphical user interfaces. As shown in Figure 4.2, there are four main file types in rrLCA 1.0, including a master workbook, a generic LCA workbook, five module add-ins, and input files.

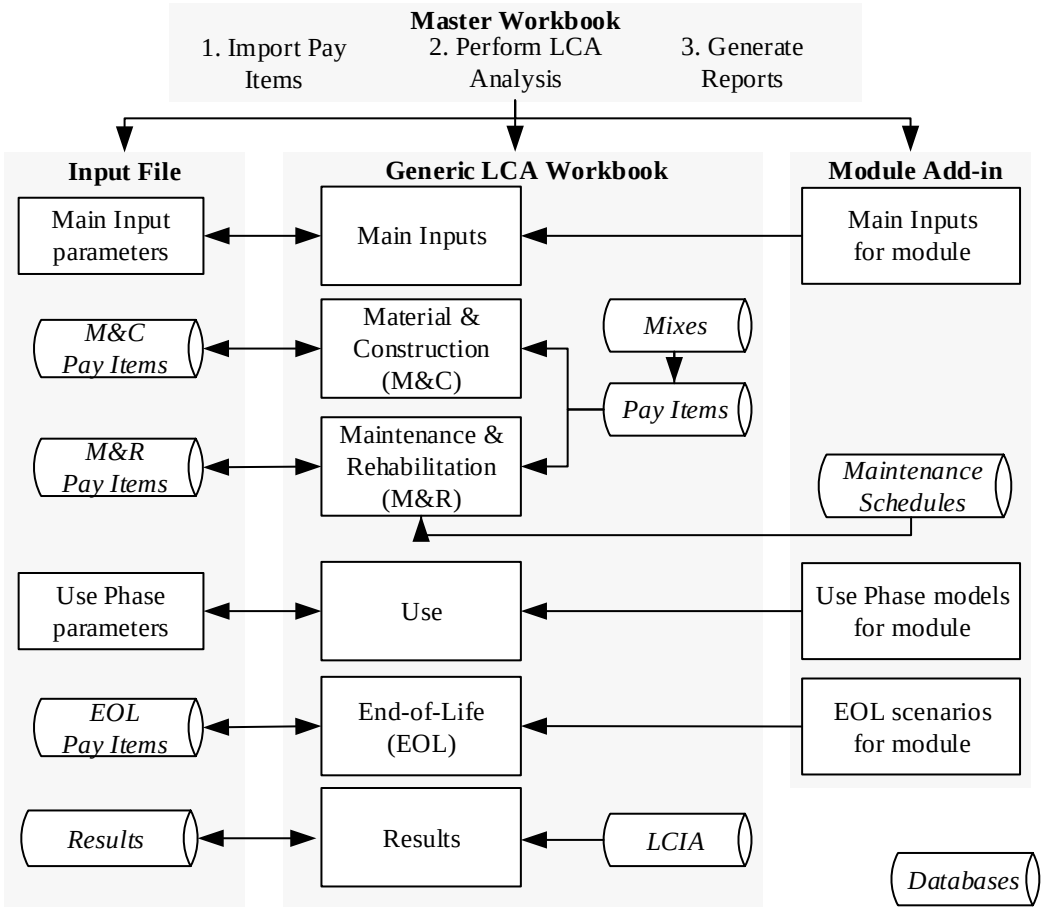


Figure 4.2: Software schematic of roadway/roadside LCA tool.

The master workbook hosts the three main functions of the LCA tool, including importing pay items for a project, performing an LCA analysis, and generating reports. The first function allows an agency to easily take an existing list of bid tabulations from a new (as-designed) or completed (as-built) contract and sort the pay items by module type. The sorted pay items are then saved in their respective module input

files to be used in new LCA analyses. The second function allows the user to pick a module type, load an existing module input file or create a new one, and progress to the generic LCA workbook with the appropriate module add-in loaded to conduct an LCA analysis. All user inputs in the LCA analysis are saved directly in a project input file. The final function allows the user to create a variety of reports based on the LCA analysis results created from the previous function. The reports can be for single modules or a compiled set of modules (i.e., a project). The reports can also show results for multiple alternative designs of the same module type or project. All results are reported per project as well as per functional unit of the module.

Each module's life-cycle is divided into four stages in the software, which includes materials and construction (M&C), maintenance and rehabilitation (M&R), use-phase, and EOL. Thus, a generic LCA workbook was developed that contains the basic framework for the LCA analysis. The generic LCA workbook ensures a consistent experience for the user when analyzing any of the five roadway/roadside elements; the generic framework also ensures that a consistent methodology is followed throughout all aspects of the LCA. Five add-in files, one for each module, are then used to provide any additional module-specific elements needed to supplement the generic LCA workbook. These include, for example, main inputs and maintenance schedules for each module as well as use-phase models for the pavement, drainage, and lighting modules.

4.6 Inventory Analysis

A large portion of the LCI databases used in this LCA study are discussed in detail in Chapters 2 and 3; thus, only a brief summary will be given in this section. Across all roadway/roadside modules, more than 1000 distinct unit processes are considered in the software, including processes related to materials, operations, transportation, and equipment. It should be noted that the databases implemented in rrLCA 1.0 are actually "LCIA" databases because impact assessment of the unit processes is performed prior to their being included in rrLCA 1.0 to reduce the number of calculations in the software.

4.6.1 Data collection and modeling

The data used in this LCA study include both primary and secondary data. Primary data considering plant and facility operations for fuel and electricity usage were collected in 2012-2013 from industry contractors associated with Illinois Tollway via questionnaires (Kang, 2013). In addition, primary data are also collected for each case study project and analyzed. These primary data include information about the pay items used, mix designs (including hauling distances), traffic levels, dimensions, and other physical attributes of the projects. The information for the case studies was taken directly from contract documents and drawings, historical Illinois Tollway mix design databases, and traffic reports.

Secondary data were also compiled from various sources such as industry reports, government reports, software, and most notably commercial LCI databases. These data were necessary to fill in gaps, account for upstream processes, and ensure that a comprehensive list of inventory data was considered. A schematic of the general LCI modeling approach is shown in Figure 4.3.

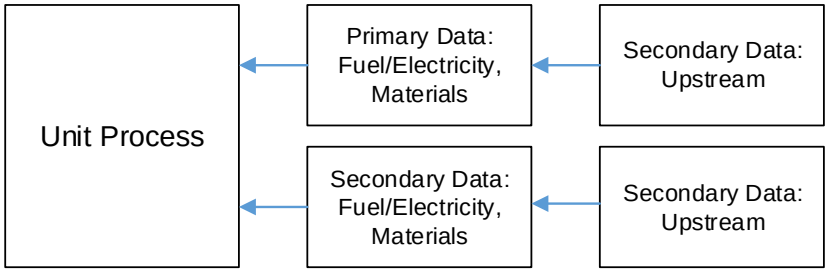


Figure 4.3: General LCI modeling approach.

The primary and secondary data were then used to create inventory models in SimaPro 8.2, a commercial LCA software, for each unit process needed in the LCA study. Finally, inventory models related to on- and off-road vehicles for hauling and construction, respectively, were modeled using U.S. EPA's MOVES2014 and NONROAD2008 software that are able to simulate vehicle emissions for Illinois-specific climatic and other conditions. Further details regarding these models can be found in previous works (Al-Qadi et al., 2015; Kang et al., 2014).

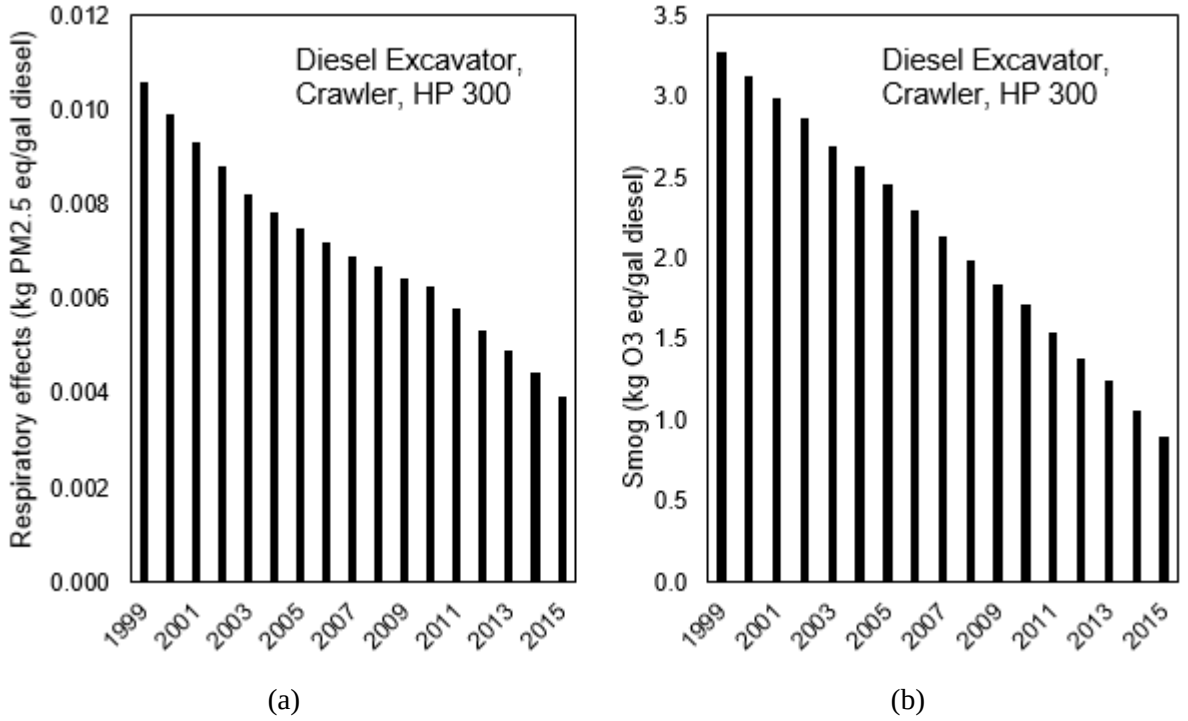
In addition, in the LCA study, each material unit process is associated with a generic EOL category (e.g. asphalt, concrete, steel, etc.). For each of these categories, four EOL scenarios are possible: landfill, recycle off-site, recycle on-site, and reuse. For all of these scenarios except recycle on-site, the remaining material may be demolished and/or removed and transported off-site. Following the cut-off rule for EOL decided in the goal and scope, all other processes are considered to be part of the next system except for impacts from the landfill scenario. It is assumed that the removed construction materials are transported to inert material landfills because hazardous wastes only comprise a small percentage of construction and demolition waste in landfills (McGregor et al., 1993). Thus, only impacts from handling the material within the landfill from default US-EI 2.2 processes are considered.

4.6.2 Progressive inventory databases

Multiple databases were included in the LCA tool to reflect different time periods (refer to Al-Qadi et al., 2015 for additional details). For unit processes related to material production and plant operations, a baseline and current database were differentiated based on electricity and fuel inputs. Electricity input was based on grid mixes from the year 2000 for baseline processes and from the year 2010 based on current

processes. For fuel-related inputs in the baseline unit processes, the fuel quantities were all increased by a default 2.0% to represent an improvement in emissions over time.

In addition, equipment databases from 1999 to 2015 as modeled using Illinois-specific conditions in NONROAD2008 were included to accommodate the average change in fuel efficiency and engine technology over time. NONROAD simulations model the implementation of emissions tiers and new equipment over time, resulting in decreases in certain air pollutants over time. For example, Figure 4.4Figure 4.4, shows the change in respiratory effects (affected by CO, NO_x, PM, and SO_2) and smog (affected by NO_x) per gallon of diesel consumed for a 300 horsepower (HP) crawler-type excavator from the years 1999 to 2015. A 63% decrease in respiratory effect and a 73% decrease in smog from 1999 to 2015 is estimated.



(a) (b)

Figure 4.4: Environmental impacts related to (a) respiratory effect and (b) smog over time for a crawler-type excavator of 300 HP.

4.6.3 Relating of unit processes to functional unit

A key design concept in the software is the use of pay items, which are used in the M&C, M&R, and EOL stages (see Figure 4.2). Pay items are the foundation of the LCA software and analysis because agencies use pay items as the basis for their contracting process. Thus, the pay items in the LCA software define how unit processes are related to the product system and are defined by general characteristics (e.g., unit, material wasted, cost, year, and productivity) as well as materials, equipment, and mix designs required. A

schematic showing the components of a pay item and how pay items relate to the overall functional unit is given in Figure 4.5.

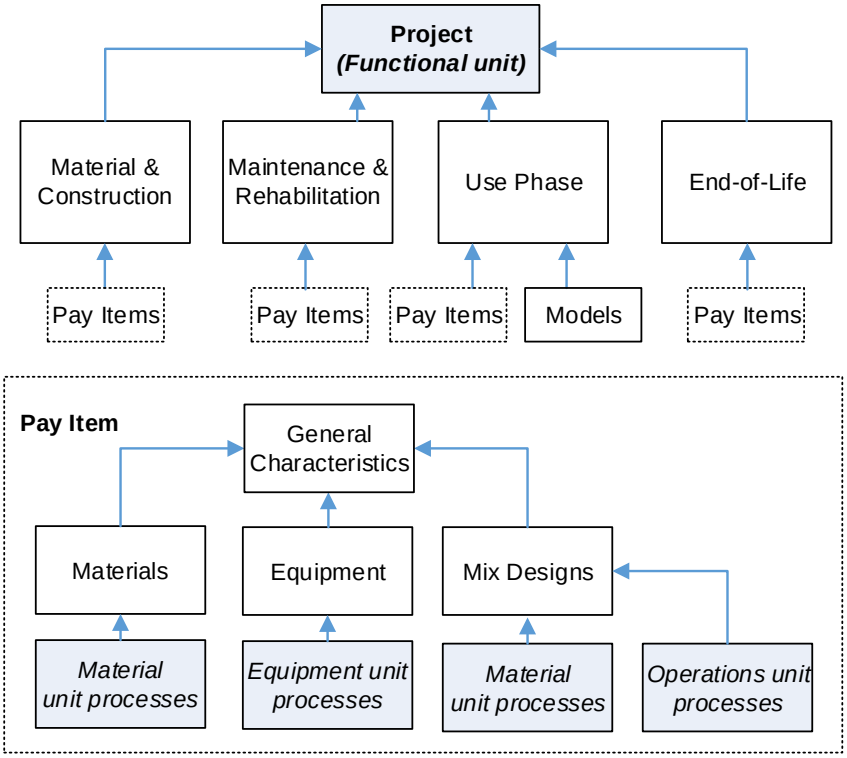


Figure 4.5: Schematic of relating unit processes to the functional unit.

4.7 Impact Assessment

4.7.1 Environmental metrics

The four major quantitative outputs from the LCA study include total primary energy (TPE), primary energy as fuel (PEF), GWP), and single score (SS). TPE, often called cumulative energy demand, includes all energy that is embodied as a fuel (e.g., diesel, natural gas) as well as energy that is embodied as a material (e.g., petroleum products such as plastics, asphalt binder, often referred to as feedstock energy), whereas PEF only includes the first component mentioned. GWP, also known as greenhouse gas emissions, is defined as the level to which emissions contribute to global warming. GWP is determined using EPA's TRACI 2.1. SS is a normalized (Bare et al., 2006) and weighted (Lautier et al., 2010) indicator that includes all ten TRACI impacts, with the resulting unit-less parameter reported in "points." It must be noted that the weighting given to the SS is subjective, though the weighting values developed by National Institute of Standards and Technology (NIST) are specific to the context of the U.S. Thus, one should use caution in interpreting the SS, knowing that it represents a simplified compilation of ten environmental impact

categories that have been weighted subjectively. A summary of the normalization and weighting factors are included in Table 4.2.

Table 4.2: TRACI 2.1 Impacts with Normalization and Weighting Factors

Impact category	Unit	Normalization	Weighting
Ozone depletion	kg CFC-11e	6.20	0.024
Smog	kg O_3e	0.000718	0.048
Acidification	kg SO_2e	0.0110	0.036
Fossil fuel depletion	MJ surplus	0.0000579	0.121
Eutrophication	kg Ne	0.0463	0.072
Respiratory effects	kg PM2.5e	0.0412	0.108
Non carcinogenics	CTUh	952	0.060
Carcinogenics	CTUh	19,706	0.096
Ecotoxicity	CTUe	0.0000905	0.084
Global warming	kg CO_2e	0.0000413	0.349

Finally, a number of other LCI-based results are also reported in the LCA that are relevant to a local transportation agency. These results include percentage of non-renewable versus renewable resources, percentage of non-recycled versus recycled content, and transportation intensity (as measured in short ton-mile). Each material unit process in the LCI databases is assigned as either "recycled" or "non-recycled" and "renewable" or "non-renewable" to calculate the first two percentages by tonnage. Transportation intensity represents tonnage and distances specified at the project-level, including those from material-to-site, material-off-site, material-to-plant, plant-to-site, and equipment-to-site.

4.7.2 Pay item impact calculation

After all of the inputs have been satisfied by the user, the software compiles a list of all pay items for all relevant stages of the module's life-cycle. The environmental impacts are calculated for each pay item, after which module-specific use-phase results are added as needed.

The pay items are calculated using a bottom-up approach by aggregating impacts from the correct quantity of unit processes defined in each pay item. The total impacts for a pay item p of one unit can be calculated using Equation (4.1), where E^{mat} is defined as impacts from material production, $E^{trans,mat}$ from material transportation, $E^{transp,site}$ from site transportation, E^{equip} from equipment, $E^{transp,equip}$ from equipment transportation, and E^{oper} from operations.

$$E_p = E_p^{mat} + E_p^{trans,mat} + E_p^{transp,site} + E_p^{equip} + E_p^{transp,equip} + E_p^{oper} \quad (4.1)$$

The impacts are furthered defined in Equations (4.2) through (4.7), where:

- I_m^{mat} is the unit material impact for each material m in the set of materials M_p in pay item p, $X_{m,p}^{mat}$ is the quantity of material m per unit pay item,

- $I_{t_{m,p}}^{transp}$ is the unit impact for transportation mode t (e.g. truck, barge, rail, etc.) per short ton-mile of material m of pay item p,
- F_m is conversion factor from the original unit of the material m to short tons,
- $D_{m,p}$ is the transportation distance for material m,
- $I_{t_{s,p}}^{transp}$ is the unit impact for transportation mode t per short ton-mile of mix s of pay item p,
- $X_{s,p}^{mix}$ is the quantity in short tons of mix s required per pay item unit,
- $D_{s,p}$ is the transportation distance for mix s,
- eff_e is the fuel efficiency (gallon per hour) of equipment e adjusted by the number of equipment used in the pay item $N_{e,p}$ and the percentage of time the equipment is not in use $U_{e,p}$ (i.e. down time where no emissions are released),
- I_e^{equip} is the unit environmental impact of equipment e per gallon, $I_{t_{e,p}}^{transp}$
- is the unit impact for transportation mode t (e.g. truck, barge, rail, etc.) per short ton-mile of equipment e of pay item p,
- W_e is the weight in short tons of equipment e, and
- $D_{e,p}$ is the transportation distance for equipment e.

$$E_p^{mat} = \sum_{m=1}^{M_p} I_m^{mat} \times X_m^{mat} \quad (4.2)$$

$$E_p^{transp,mat} = \sum_{m=1}^{M_p} I_{t_{m,p}}^{transp} \times F_m \times X_{m,p}^{mat} \times D_{m,p} \quad (4.3)$$

$$E_p^{transp,site} = \sum_{s=1}^{S_p} I_{t_{s,p}}^{transp} \times X_{s,p}^{mix} \times D_{s,p} \quad (4.4)$$

$$E_p^{equip} = \frac{1}{prod_p} \sum_{e=1}^{E_p} I_e^{equip} \times eff_e \times \left(1 - \frac{U_{e,p}}{100}\right) \times N_{e,p} \quad (4.5)$$

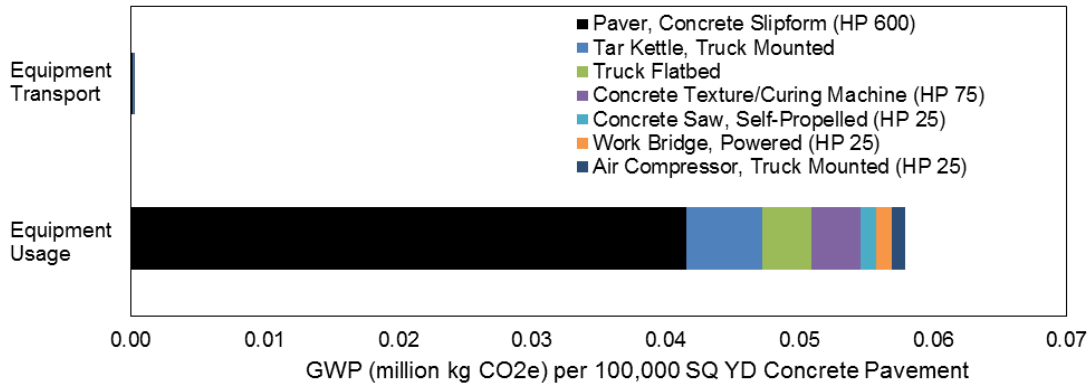
$$E_p^{transp,equip} = \sum_{e=1}^{E_p} I_{t_{e,p}}^{transp} \times W_e \times D_{e,p} \times N_{e,p} \quad (4.6)$$

$$E_p^{oper} = \sum_{o=1}^{O_p} I_o^{oper} \times X_{o,p}^{oper} \quad (4.7)$$

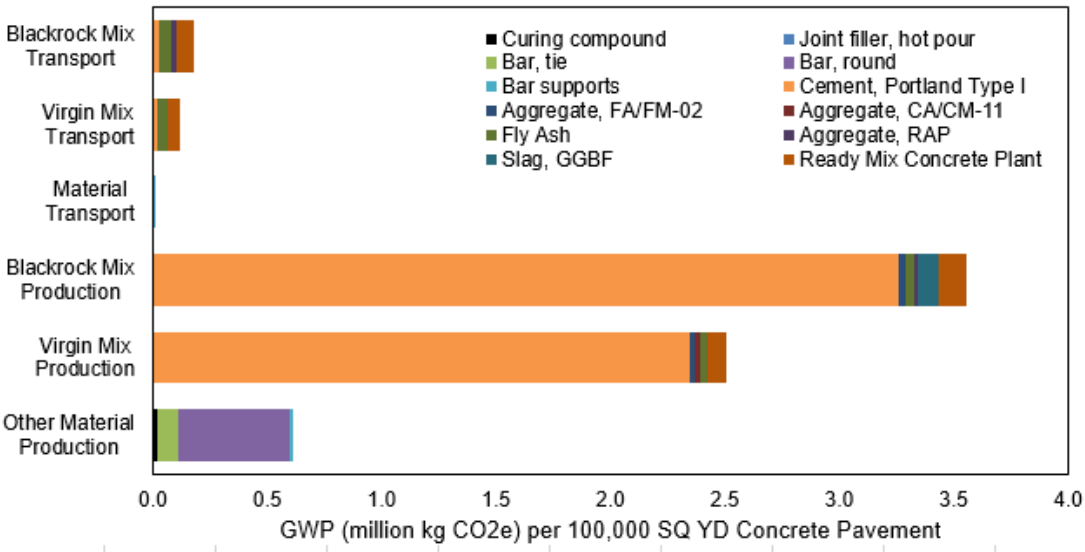
The total project impacts are then given in Equation (4.8), where the pay item impacts E_p for each pay item p are multiplied by the pay item quantity $X_p^{payitem}$ adjusted to include additional impacts for producing a percentage of the material that is ultimately not used in the product, $waste_p$. Any module-specific impacts, $E^{module-specific}$, are than added to the overall impacts.

$$E_{project} = \sum_{p=1}^{P} \left[X_p^{payitem} \times \left(1 + \frac{waste_p}{100}\right) \times E_p \right] + E^{module-specific} \quad (4.8)$$

An example of a pay item's environmental impacts are shown in Figure 4.6 for 100,000 square yards (yd^2) of a composite Portland cement concrete pavement.



(a)



(b)

Figure 4.6: Contribution of (a) equipment usage and (b) material production to the GWP per 10,000 square yards of composite Portland cement concrete pavement pay item.

The intermediate impacts for each unit process included in the pay items is individually demarcated in the figure. For this pay item, it is clear that material production is the highest contributing process type, followed by plant operations, transportation and mobilization, and finally equipment. Regarding equipment, the two paving machines contribute approximately 72% of the total GWP associated with equipment, while

mobilization accounts for 0.4%. Note that the mobilization of equipment is a one-time impact that varies depending on the volume of work (i.e. 100,000 yd^2). For this pay item, a breakeven point where the equipment usage and transportation GWP are equivalent would be approximately 443 yd^2. The largest GWP contributors among materials are related to the production of Portland cement (80%) and steel (8%). Material transportation, while volume dependent, contributes approximately 4% of the total GWP attributed to material processes for this pay item.

4.8 Interpretation

The three steps required for interpretation in ISO14044 include identifying significant issues and results, evaluating the study, and giving conclusions, limitations, and recommendations. Thus, a presentation of the results of various pavement case studies will be presented first, followed by an evaluation of the study, and finally a discussion of concluding remarks.

4.8.1 Project background

A series of 14 pavement projects[8] from past Illinois Tollway contracts were analyzed using rrLCA 1.0. These projects spanned 15 years from 1999 to 2014 with contract bids ranging from $6.7 to $48.8 million. The collection of contracts included nine widening and reconstruction projects, three new construction projects, and two resurfacing/rehabilitation project. A summary of major characteristics of each project are listed in Table 4.3, where traffic is given as average annual daily traffic (AADT) for each relevant direction (i.e., northbound [NB], southbound [SB], eastbound [EB], and westbound [WB]).

To represent the projects as closely as possible, primary data related to the actual pay items, traffic parameters, geometries, mix designs, plant distances, and costs were collected. It was assumed that the traffic growth for the project was constant over the analysis period and assigned based on the historical and predicted growth rate for the entire toll road from 2000-2040. In addition, as the projects were analyzed over their design lives of 44 to 75 years, it was found that many of these road segments were estimated to reach their traffic capacities (based on a maximum 2400 vehicles per hour per lane limit) before the end of their respective analysis periods. At this point, a widening or diversion would be required, but in these case studies, the traffic was curtailed and remained at the capacity without growth or additional widening for the rest of the analysis period.

The LCA results of the projects are presented in four different formats: total project results, results grouped by component, detailed project results, and results from other environmental metrics.

[8] Wonjae Yoo performed the analysis for six of these projects.

Table 4.3: Summary of Project Details

Year	Contract	Length (mi)	Analysis Period[9]	AADT (2013)	% Truck	Cumulative VMT (mil)	Cost ($M)[10]	Pavement Pay Items	Project Type[11]	Number of Lanes	Pavement Type
1999	723	5.1	44 years; 2 overlays	51,475 EB; 50,720 WB	11.2	5.8 EB; 5.9 WB	$12.5 of $13.2	19	WR	2 to 3	12-inch JPCP
2001	8101	12.8	58 years; 4 overlays	70,864 NB; 70,968 SB	17.1	21.4 NB; 21.5 SB	$6.4 of $6.7	30	RR	4	3-inch HMA
2004	5198	4.6	78 years; 3 overlays	67,005 EB; 67,655 WB	9.1	13.6 EB; 13.1WB	$31.0 of $36.7	31	WR	3 to 4	12-inch CRCP
2006	7710	1.42	62 years; 3 overlays	31,720 NB; 30,960 SB	13.1	1.1 NB; 1.1 SB	$16.6 of $18.0	32	NC	0 to 3	12-inch JPCP
2006	7713	1.72	62 years; 3 overlays	34,275 NB; 33,325 SB	13.1	2.4 NB; 2.4 SB	$13.9 of $15.0	27	NC	0 to 3	12-inch JPCP
2007	5228	2.6	62 years; 3 overlays	61,270 SB	13.8	5.0 SB	$8.8 of $10.0	16	WR	3 to 4	12-inch JPCP
2007	5542	5.0	75 years; 4 overlays	24,120 EB	29.4	9.3 EB	$10.2 of $11.3	18	WR	2 to 3	12 & 15-inch HMA
2008	5540	7.6	75 years; 4 overlays	24,860 EB	11.3	9.7 EB	$35.6 of $39.5	29	WR	2 to 3	12 & 15-inch HMA
2009	5543	5.0	75 years; 4 overlays	23,380 WB	11.3	5.7 WB	$28.1 of $44.3	36	WR	2 to 3	12 & 15-inch HMA
2009	5541	7.6	75 years; 4 overlays	25,340 WB	29.4	5.8 WB	$21.0 of $26.3	25	WR	2 to 3	12 & 15-inch HMA
2013	4047	29.8 (4.62)[3]	58 years; 4 overlays	56,710 NB; 57,620 SB	6.9	12.5 NB; 12.6 SB	$15.2 of $17.1	39	RR	4	SMA & WMA 2.5-inch overlay
2013	4066	0.3 (1.2)[12]	62 years; 4 overlays	4,100 NB	22.1	0.15 NB	$6.3 of $29.5	26	NC	0 to 2	12-inch JPCP
2013	4077	3.9	62 years; 3 overlays	28,460 EB	13.3	4.0 EB	$19.7 of $32.4	24	WR	2 to 3	12-inch JPCP
2013	4133	8.6	62 years; 3 overlays	19,240 WB	20.3	6.7 WB	$40.7 of $48.5	21	WR	2 to 3	11.25-inch JPCP composite

[9] This column includes in parenthesis the number of overlays regarding only mainline HMA or SMA overlays (not shoulder overlays).
[10] This column includes the cost of pavement–related items out of the total project cost.
[11] The types of projects are defined as WR (widening and reconstruction), NC (new construction), and RR (resurfacing/rehabilitation).
[12] The number in the parentheses indicates the actual (effective) length applied in the LCA. The other sections of the roadway segment were for patching activities.

4.8.2 Total project results

The total project results for each of the four main impacts (i.e., SS, GWP, TPE, and PEF) are discussed. In Figure 4.7, the total results per functional unit for each project are given along with the percentage that each life-cycle stage contributes to the impacts. The projects are grouped by project type, which include PCC widening and reconstruction as "A", full-depth HMA widening and reconstruction as "B", new PCC mainline and ramp construction as "C", and finally HMA resurfacing/rehabilitation as "D."

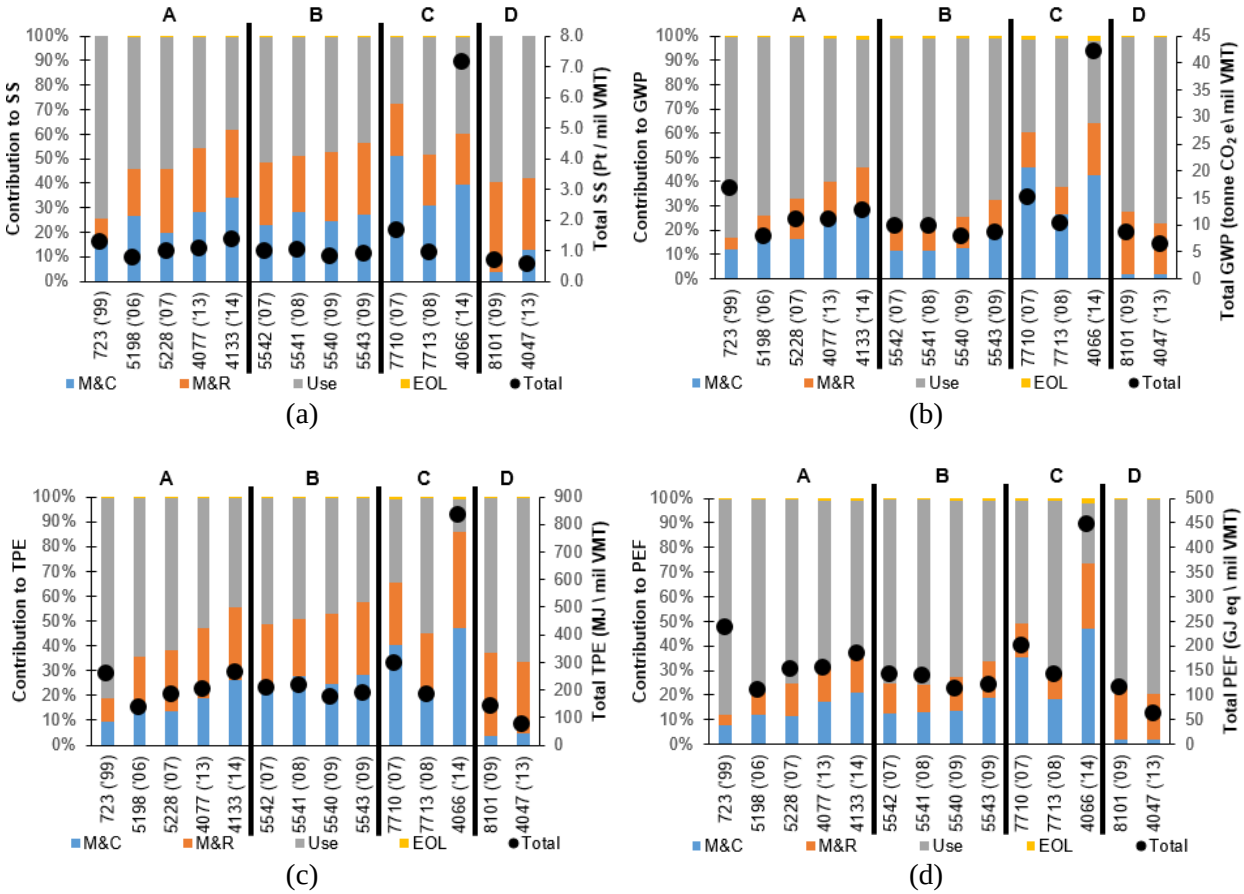


Figure 4.7: Total project results for (a) SS, (b) GWP, (c) TPE, and (d) PEF, where group "A" contains PCC reconstruction projects, "B" full-depth HMA reconstruction projects, "C" new PCC construction, and "D" HMA resurfacing project.

It should be noted that all of the projects have unique traffic levels, which affect the percentages shown. The "A" projects have a wide range of traffic levels (19,000 – 60,000 AADT), the "B" and "C" projects have similar traffic levels (24,000 – 35,000 AADT) with the exception of the new ramp construction in project 4066 (4,100 AADT), while the "D" projects have generally higher traffic levels (57,000 – 70,000 AADT). It should also be noted that the results for the HMA reconstruction project are

similar because these contracts are actually part of a series of reconstructions along an adjacent segment of the Jane Addams Memorial Tollway.

In general, the results for each type of project (i.e. reconstruction, new, and resurfacing) are similar with the exception of 723. The M&R and M&C stages in the reconstruction projects contribute a similar percentage for each impact, aside from 723, which only has two overlays and thus a smaller M&R impact. The M&C stage tends to have larger impacts than M&R for new projects ("C"), while the two stages are more similar in impacts contributed for reconstruction projects ("A" and "B"). Also, for all projects, the use-phase stage contributes the most to fuel-related GWP and PEF impacts. However, it should be noted that the use-phase contains the most uncertainty out of all of the life-cycle stages and its exact contribution to the overall LCA results may depend heavily on assumptions. For HMA reconstruction projects ("B"), the use-phase stage contributes considerably more than other stages for the fuel-related GWP and PEF impacts as compared with SS and TPE. This is due to the inclusion of asphalt binder feedstock in TPE.

The total impacts per functional unit are also shown in Figure 4.7 and indicated by the black dots on the graphs. These results tend to follow the trend of the M&R and M&C stages because the total impacts are normalized by VMT (i.e., the use-phase). However, the exception to this trend is again 723, which is a JPCP-20 pavement. The IRI of this pavement was predicted to reach almost 200 inch/mile before the pavement's rehabilitation, causing a corresponding increase in impacts due to the use-phase.

Overall, the patterns among the environmental impacts for each project type are similar, with the exception of the new PCC ramp construction (4066). The new PCC ramp construction project is the outlier out of all of the projects because it has the highest M&C impacts as well as the lowest traffic level; thus, the 4066 has the highest per million VMT impacts. While the amount of VMT is expected to reflect the structural design of the pavement, the ramp serves a different purpose than a mainline pavement and should not be directly compared to the other project types by functional unit.

In general, the percentage contributions for GWP and PEF are similar, while the percentage contributions for SS and TPE are similar. The results also vary over time, without clear evidence of trends. Thus, it may be difficult for an agency to directly compare similar project types by only considering total environmental impacts over time. Each project has unique attributes (e.g., special pay items, design features, contract scope, traffic levels or traffic management needs) that obfuscate a straightforward comparison. Instead, comparing alternative life-cycle designs of the same roadway will allow for less independent variables in a comparative LCA analysis.

4.8.3 Results by component

While the total results may give some insight into project-by-project trends for each impact by project type, it is also useful to observe the results by major life-cycle component. To illustrate the wide range of projects

analyzed in this study, Figure 4.8 shows the average as well as standard deviations of each environmental impact per functional unit for each life-cycle stage considered in the LCA. The components of the use-phase in particular are further distinguished into impacts resulting from roughness effects, texture effects, albedo, and carbonation. As seen in Figure 4.8, the standard deviations are very large, emphasizing the large variety in results obtained in the baseline and current projects. The stage with the least amount of variation is texture due to limitations in the model (one for flexible and one for rigid pavement). The largest variations can be attributed to albedo (because it can be negative or positive) and then M&C pay items.

Even accounting for model-driven limitations, the range of impacts seen can provide insight into the potential for improvement in each major life-cycle component. While M&C impacts have the largest variation, agencies also have the greatest amount of control over these impacts because they are based directly on bid items. Roughness and M&R impacts also vary quite widely, and coincidentally, these components are also significantly related to each other. Agencies also have a large amount of control over M&R and also roughness in terms of deciding life-cycle maintenance and rehabilitation schedules. Therefore, while a portion of the variation in impacts must be attributed to contract requirements, an agency also may consider investigating and setting policies that can influence the life-cycle components that they exhibit a large amount of control over.

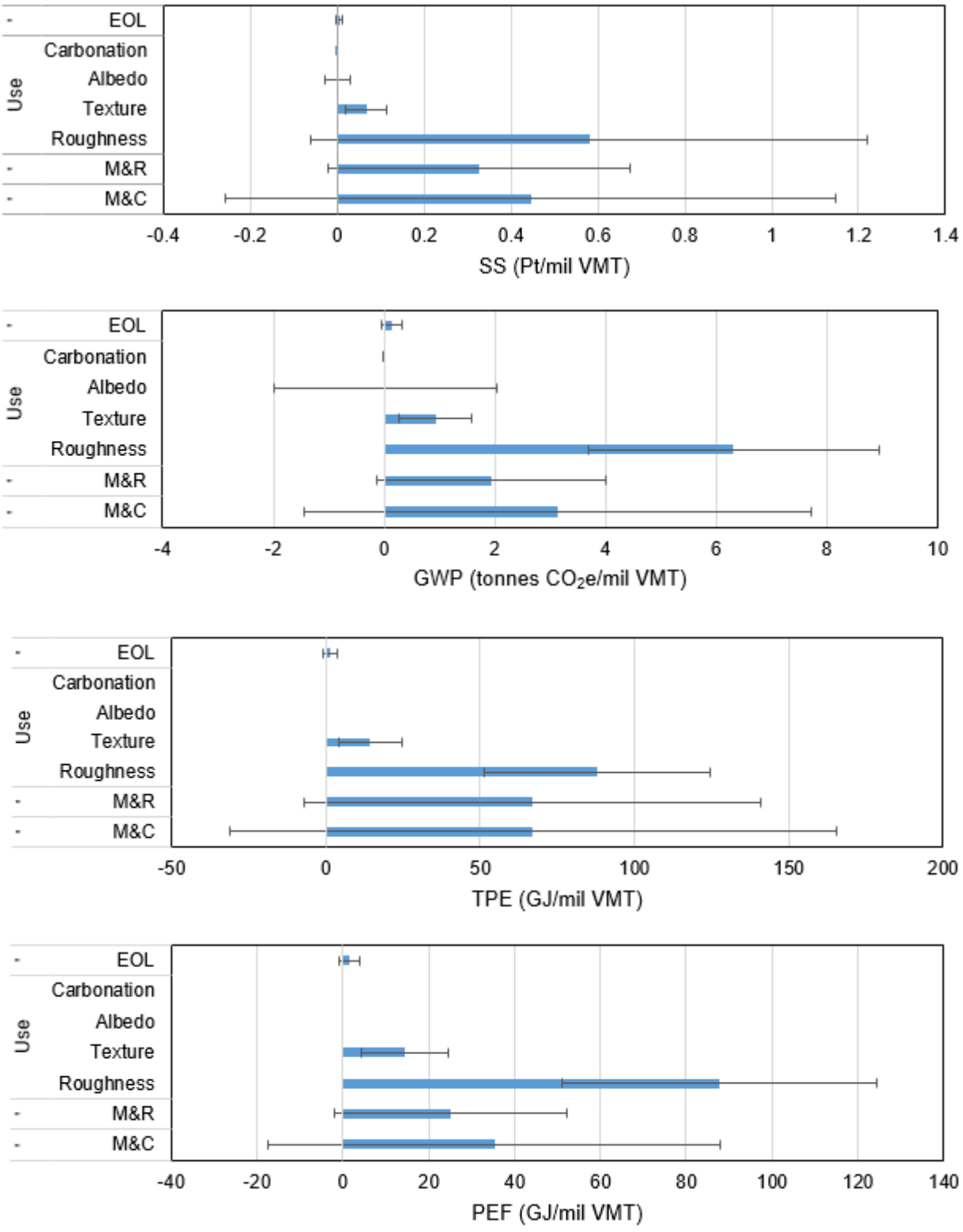


Figure 4.8: Range of results per millions VMT results for SS, GWP, TPE, and PEF for major processes for all projects.

4.8.4 Detailed project results

A detailed project-by-project analyses of the results is also necessary due to the unique features and context of each project. In this work, five projects have been selected for in-depth discussion. These projects cover each of the project types that were used to categorize the projects in the total project results.

4.8.4.1 Widening and reconstruction – HMA

The full-depth HMA widening and reconstruction chosen is from contract 5540, which was completed in 2009 on the eastbound of the Jane Addams Memorial Tollway (I-90/I-39/US 51). Two existing PCC lanes were removed to reconstruct two 12-inch full-depth HMA lanes and one new 15-inch full-depth HMA lane was added. A summary of the contributions of each life-cycle stage and top items to the environmental indicators can be seen in Figure 4.9. The contribution of the use-phase was the highest for all of the indicators (47 – 73%), with M&C and M&R following. The top four contributing pay items all were related to HMA, including initial full-depth construction and subsequent HMA surface and binder overlay paving for the four 4-inch overlays considered in the 75-year analysis period. In addition, the contribution of materials and construction (i.e. M&C and M&R stages) to TPE is significantly less than that for GWP and PEF for this project. GWP generally correlates strongly with fuel consumption or PEF, but the addition of primary energy in material form, and specifically asphalt binder feedstock in this case, significantly increases the share of TPE corresponding to M&C and M&R.

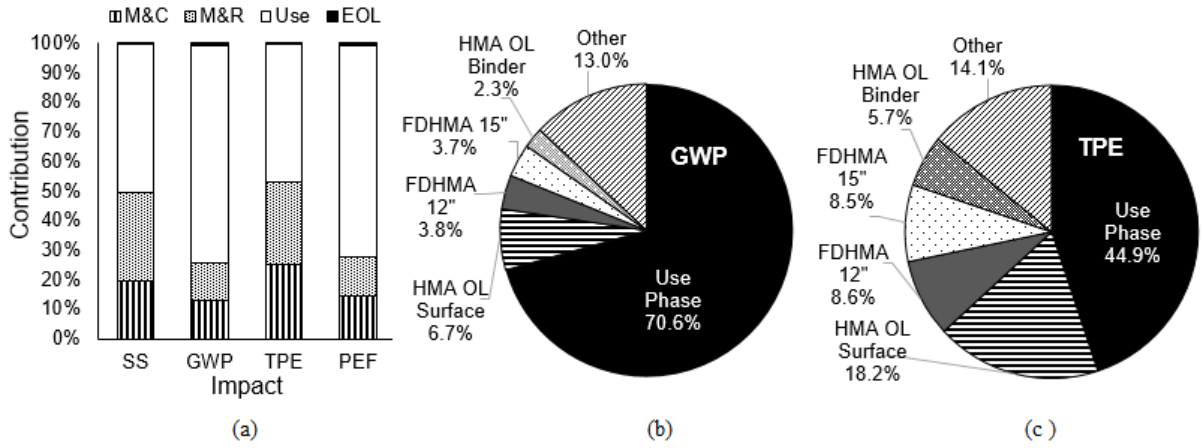


Figure 4.9: Contributions of (a) life-cycle stages to environmental impacts and top four pay items to (b) GWP and (c) TPE for HMA widening and reconstruction construction project 5540.

4.8.4.2 Widening and reconstruction – PCC

Two PCC reconstruction projects are included in this detailed analysis, with one older project from 1999 and one newer project from 2013. Both projects included a widening from two existing PCC pavement

lanes to three new JPCP pavement; however, 723 on the Ronald Reagan Memorial Tollway (I-88) used a conventional JPCP while the newer project on the Jane Addams Memorial Tollway (I-90/I-39/US 51) used a composite or two-lift JPCP with a 3-inch virgin concrete over a 9 or 10-inch black rock ternary concrete. On average, the mixes in 723 contained 451 lb/yd^3 Portland cement and 141 lb/yd^3 fly ash while the black rock mixes in 4077 contained 375 lb/yd^3 Portland cement, 145 lb/yd^3 fly ash, and 60 lb/yd^3 slag. The analysis periods and thus design of the systems were also different for 723 (44 years with two overlays) and 4077 (62 years with three overlays). Summaries of the environmental impact contributions from these two projects are included in Figure 4.10 and Figure 4.11.

The distribution of environmental impacts are noticeably different in 723 and 4077 even though they both represent PCC widening and reconstruction projects. Two important differences between these projects that prevent them from being directly compared are related to traffic volume (i.e. 4077 is half that of 723) and future scheduled activities (i.e. 4077 includes three overlays while 723 only two). Thus, the contribution of the use-phase for 723 was higher at 74 – 88% while that for 4077 was 48 – 68%. In addition, the TPE contribution of HMA overlays for 4077 is significantly higher due to the presence of an additional HMA overlay constructed over the analysis period for the newer project. One item that may be more directly compared are the per unit impacts of the JPCP and composite JPCP pavement pay items. For the 723 project, these were 92 kg CO2e/yd^3 for GWP and 766 MJ/yd^3 for TPE and correspondingly 82 kg CO2e/yd^3 and 709 MJ/yd^3 for 4077, respectively. The reduction in impacts for 4077 is expected due to the higher amount of recycled and supplemental cementitious materials used in the composite JPCP pavement.

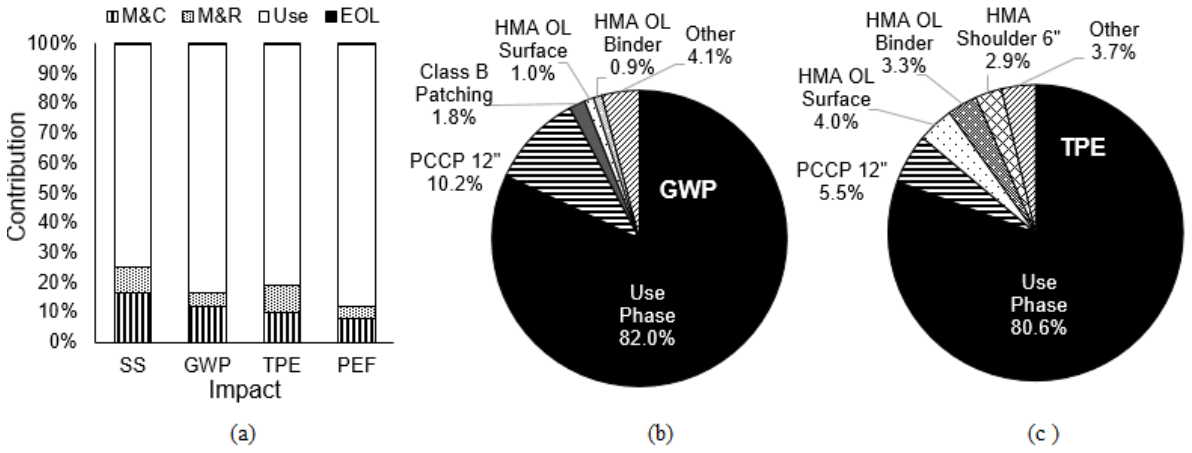


Figure 4.10: Contributions of (a) life-cycle stages to environmental impacts and top four pay items to (b) GWP and (c) TPE for PCC widening and reconstruction construction project 723.

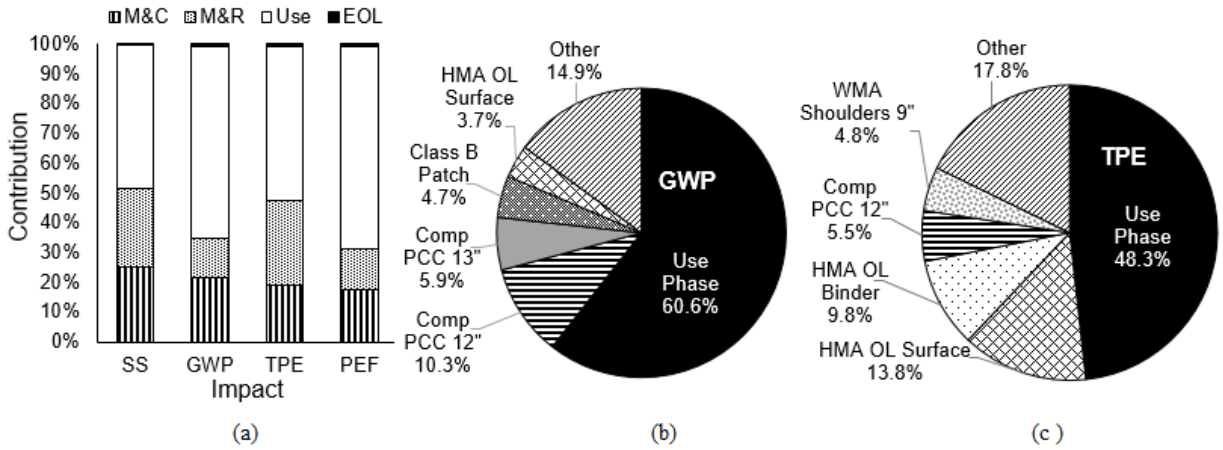


Figure 4.11: Contributions of (a) life-cycle stages to environmental impacts and top four pay items to (b) GWP and (c) TPE for PCC widening and reconstruction construction project 4077.

4.8.4.3 New construction – PCC

The selected new construction project, 7713, was completed as part of the South Extension on Veterans Memorial Tollway (I-355) beginning in 2006. It involved the construction of three 12-inch JPCP lanes in two directions, while subsequent M&R activities were assumed to include three overlays. A summary of the environmental impact analysis can be seen in Figure 4.12. The results of this analysis are similar to that of the 4077 widening and reconstruction project with JPCP due to similar traffic levels, number of lanes, and M&R schedules. The contribution of initial construction for 4077 ranged from 16 – 27%, which is similar to that for 7713 which ranged from 18 – 31%. While a new construction may involve additional earthwork and site preparation, the impacts from the initial construction of the PCC pavement itself and subsequent HMA overlays seem to overshadow additional impacts from other pay items.

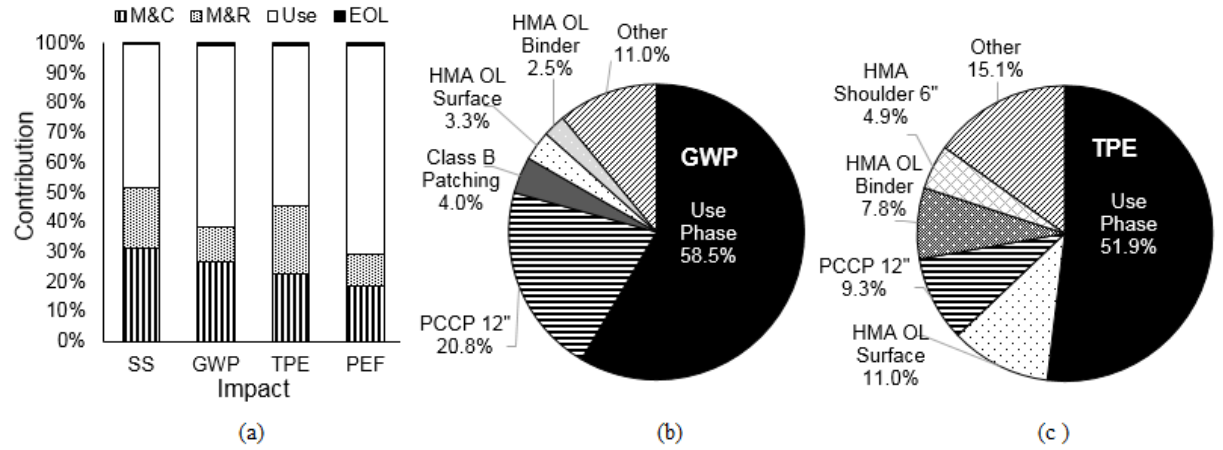


Figure 4.12: Contributions of (a) life-cycle stages to environmental impacts and top four pay items to (b) GWP and (c) TPE for new construction project 7713.

4.8.4.4 Resurfacing – HMA

The selected resurfacing project, 4047, was completed in 2013, and its scope included resurfacing, patching and bridge repair throughout the entire Veterans Memorial Tollway (I-355). This project divided the 29.8-mile tollway into four zones, where zones A, B, and C were for resurfacing and patching at near the highway interchanges and zone D was for simple patching on the mainline and bridge repairs. Thus, the effective length of 4.62 mi for zones A, B, and C was used to calculate the activities necessary for maintenance and rehabilitation as well as for traffic impacts in the use-phase. The proposed resurfacing work was 1.75-inch SMA surface and 0.75-inch WMA binder over the existing four 12-inch JPCP lanes (three mainlines and one ramp line) in each direction. Subsequent M&R activities assumed for this SMA-JPCP pavement included four overlays over a 58-year analysis period. A summary of the environmental impact results can be seen in Figure 4.13. As expected of a resurfacing job, the 4047 initial M&C contribution for the indicators was the lowest (2 – 6 %) among all projects due to its reduced scope. Consequently, the use-phase stage in this project dominates the environmental impacts at 72 – 84% of total impacts.

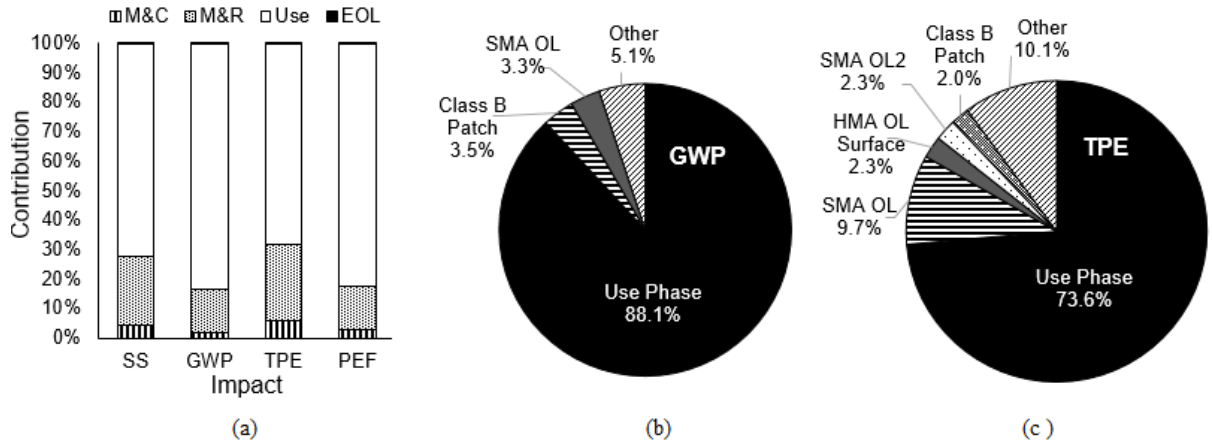


Figure 4.13: Contributions of (a) life-cycle stages to environmental impacts and top pay items to (b) GWP and (c) TPE for resurfacing construction project 4047.

The detailed project results discussed in this subsection are in fact still summaries of the full LCA results for each project. Using rrLCA 1.0, the results can be disaggregated to the smallest level so that the individual impacts of each unit process can be determined. Nonetheless, looking at more detailed results of the projects at a component/pay item level is also useful for agencies. By understanding which pay items or use-phase components contribute the most to the environmental impacts of a project and exactly how much they contribute, agencies can better identify and justify where efforts should be placed so that the most effective improvements can be made.

4.8.5 Additional results

The preceding discussions have focused on the four general environmental impacts (e.g., SS, GWP, TPE, and PEF). In addition to these impacts, transportation agencies may also be interested in targeted results for pavement construction in particular that can be very clearly influenced by the choices that they make in terms of which types of materials are used and where they come from. These metrics include percentage recycled content, percentage renewable content, and transportation intensity. As the pavement industry has come to adopt the use of sustainable materials over time, indications of this influence should be reflected in projects over time.

The percentage of recycled content used in pavement construction over the years is expected to increase due to increasing use of sustainable strategies. As seen in Figure 4.14, the percentage of recycled content ranges from 4.8% to 48.0% and increases over time, even when looking at projects by groupings. The exception to this is for group "B" (HMA reconstruction), which were essentially part of the same reconstruction and widening effort spanning multiple years. Sustainable strategies by the Illinois Tollway that have contributed to the increase in recycling include use of recycled asphalt pavement and recycled asphalt shingles in HMA as well as the use of recycled aggregate in base, subbase, and subgrade layers. By viewing such metrics over time, an agency can measure overall progress in these areas and set goals for future acquisitions.

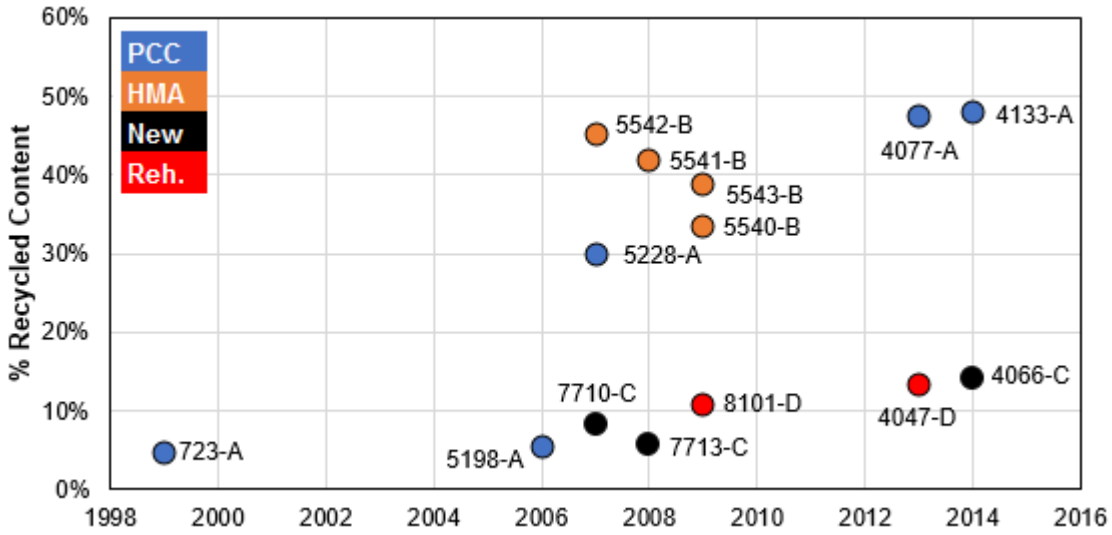


Figure 4.14: Percent recycled content for all pavement projects over time.

The progression of renewable content is next shown in Figure 4.15. Common renewable materials used in pavement construction include those derived from organic materials such as wood posts, plywood or water. Aggregates were not considered renewable materials in this study as their natural replacement takes place on a significantly longer-than-human time scale. Renewable materials may be more relevant to

the drainage and landscape modules due to seeding and soil. The percentage renewable material used is quite small and ranges from 0% to 1.3%. The percentage does increase slightly, but the trend may have more to do with the specific materials used in the contract rather than an overall gauge of renewable materials used across the pay items in the project.

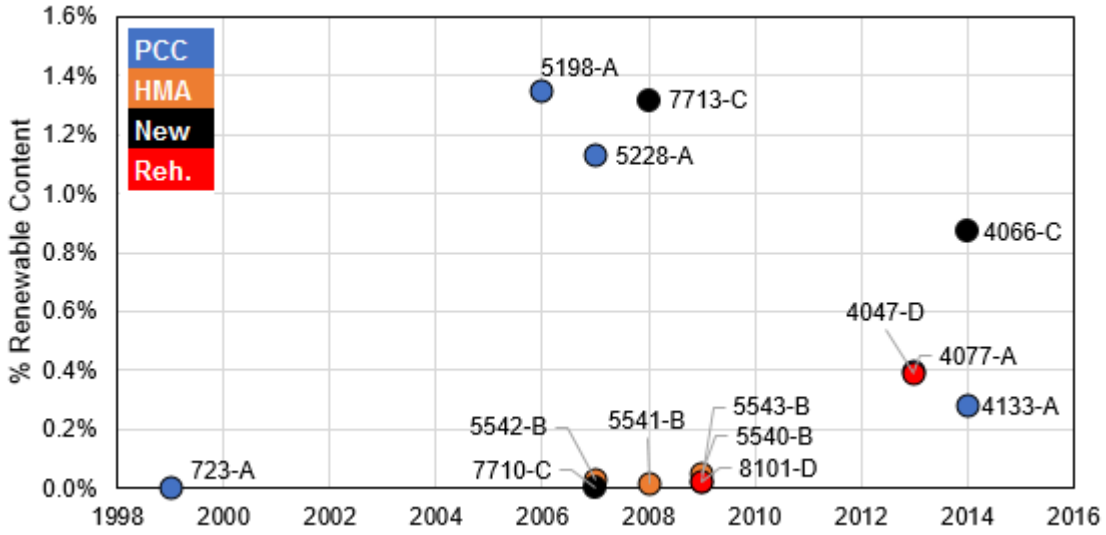


Figure 4.15: Percent renewable content for all pavement projects over time.

Finally, transportation intensity is also plotted over time in Figure 4.16. It should be noted that the units for transportation intensity are not normalized by project dimension in this analysis. This metric is measured in short-ton miles, and thus takes into account both tonnage of material hauled as well as distance.

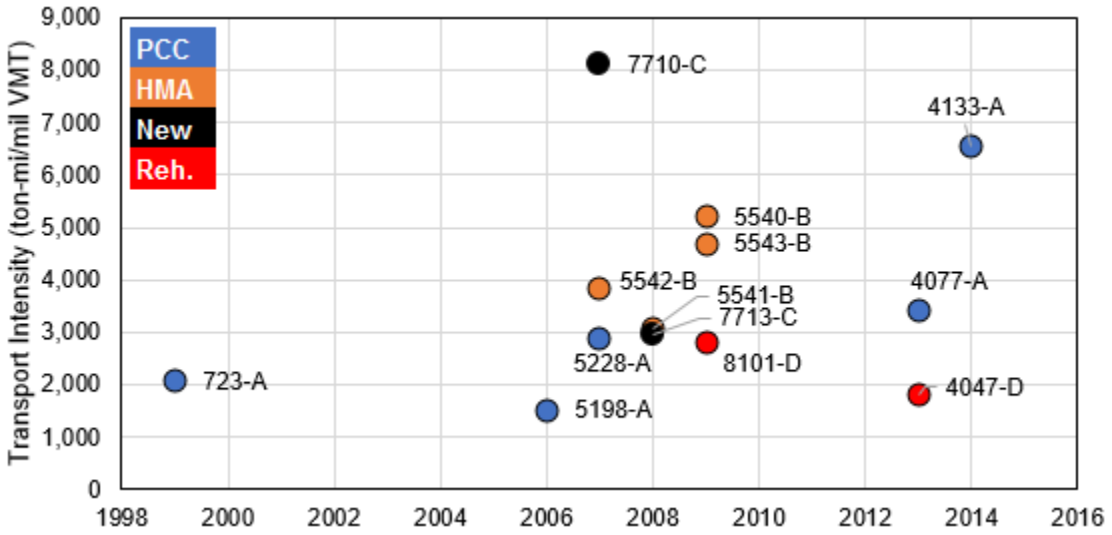


Figure 4.16: Transportation intensity for all pavement projects over time.

The trend is quite uniform over time, with the exception of 8101, and ranges from between 4.5 million and 46 million short-ton miles. The outlier, 8101, is a resurfacing project that used a 2.5-inch SMA overlays. SMA mixes use high-quality granite aggregate that are not found in Illinois. Thus, this aggregate must be haul from Wisconsin at a distance 40 to 60 mi from the plant rather than the average of 20 mi. In addition, this project also involved significant removal of existing HMA overlay during initial construction, with both of these factors contributing to the transportation intensity of over 120 million short-ton mi.

4.8.6 Evaluation

The second step in LCA interpretation is to evaluate the study for completeness, sensitivity, and consistency against the original expectations set in the goal and scope.

A summary of completeness check for the system boundaries of the study is given in Table 4.4, where all required life-cycle stages for all roadway/roadside modules are satisfied. In addition, the LCI data requirements of using regionally and temporally appropriate data are acceptable due to the user of relevant primary and secondary data as well as progressive inventory databases. The LCIA requirements for including environmental metrics relevant to an agency at a global (e.g., GWP) and local (e.g., transportation intensity) scale are also satisfied. Thus, satisfactory relevant information is included to meet the goal of the study in evaluating the environmental impact of the agency's projects over time and identifying areas where policy changes can result in benefits to the environment.

Table 4.4: Completeness Check of Software

Stage	Drainage	Landscape	Lighting	Pavement	Structures
Materials	✓	✓	✓	✓	✓
Construction	✓	✓	✓	✓	✓
Maintenance & Rehab.	✓	✓	✓	✓	✓
Use	✓	Out of Scope	✓	✓	Out of Scope
End-of-Life	✓	✓	✓	✓	✓

Regarding consistency, the methodology has been applied consistently to all modules due to the use of the generic LCA framework, quantitative cost cut-off criteria, and allocation procedures. An exception to the last methodological item is the use of different allocation methods for petroleum products (e.g., asphalt binder, diesel, and gasoline) due to the use of various secondary sources. The data were also analyzed as consistency as possible due to emphasis on utilizing data that were regionally and temporally relevant to the Illinois Tollway. Any major unit processes that were modeled or simulated in detail (e.g., asphalt binder, electricity, asphalt plants, hauling trucks, and equipment) were done so using representative parameters. Upstream data was also accounted for each unit process using the US-EI 2.2 database. Finally, established methodologies were used (e.g., TRACI 2.1, CED) via SimaPro 8.2 to calculate environmental

impacts. Thus, the goal of the agency in self-evaluating over time and identifying areas of improvement can be satisfied with the level of consistency portrayed in this LCA.

A complete evaluation of an LCA also includes analyses to investigate the effect of methodological choices, assumptions, and uncertainty on the LCA results. In this dissertation, Chapter 5 addresses sensitivity analyses in detail while Chapter 6 addresses the topic of uncertainty in detail.

4.8.7 Discussion

In this LCA, the transportation agency was interested in "self-evaluating the progress in sustainability of discrete projects over time as well as in identifying areas where changes in policy can result in greater benefits to the environment." It was shown that the rrLCA 1.0 software can provide LCA results to address this goal; however, the interpretation of results must be carefully conducted. The results were presented in a variety of manners, with each leading to an additional perspective in findings and potential implication for the agency.

There are, however, major assumptions and limitations in the LCA that must be considered in the interpretation of results and be addressed in future works. First, even though considerable effort was undertaken to collect relevant primary and secondary data as well as model unit processes, the LCI database is still limited in its ability to reflect and predict changes in impacts over time and for the Illinois region. The uncertainty inherent in any inventory database should be taken into account. Second, the traffic models in the pavement module are deterministic even though future traffic volumes and vehicle mixes are quite uncertain. The use-phase was seen to consistently contribute the highest amount of impacts out of all life-cycle stages, so accounting for uncertainty regarding traffic parameters will likely have a large influence on the overall LCA results. Third, environmental impacts from congestion during construction zones is not considered in rrLCA 1.0. Major acquisition contracts such as the ones evaluated in this work are expected to have a notable impact on the speed, driving behavior, and emissions of vehicles in construction work zones. Future work should also incorporate these effects in the LCA. Finally, in rrLCA 1.0, the modules are treated as completely independent from each other. Thus, there is no impact, for example, of the type of pavement on the drainage system unless the user manually adjusts the use-phase inputs in the drainage module. The interconnection between the modules should be further explored.

4.9 **Summary**

This chapter described the development and implementation of a roadway/roadside LCA software for Illinois Tollway. A multi-module software was developed to consider five elements of the roadway/roadside system including drainage, landscape, lighting, pavement and structures. The entire life cycle of the system from M&C, M&R, use-phase, and EOL can be analyzed for each module. The software

is based on pay items, which allows it to consider the materials, equipment and mix designs required for numerous construction activities.

In addition, fourteen pavement projects were analyzed with rrLCA 1.0 according with the agency's goal to evaluate over time the environmental impacts of major acquisition projects as well as to identify areas where agency policies can potentially bring greater benefits to the environment. These projects were taken from Illinois Tollway contracts in place between 1999 to 2014 and included acquisitions ranging from PCC and HMA widening and reconstruction, new construction, and resurfacing/rehabilitation. The results of the projects were interpreted using various representations and visualizations of the results, including total results, results by life-cycle component, detailed project results, and local project results. Each of manners of looking at the LCA results contributed additional findings and potential applications for the agency. After evaluating the completeness and consistency of the LCA, it was found that rrLCA 1.0 was sufficient to fulfill the requirements of the original goal and scope of the LCA.

Overall, the rrLCA 1.0 is a useful roadway/roadside LCA software that was created specifically to meet needs of agencies in assessing the environmental impacts of their major construction acquisitions. While the limitations of rrLCA 1.0 are clear, this LCA implementation does contribute to the current collection of pavement LCA tools due to its regional, progressive LCI databases, comprehensive in both life-cycle and roadway/roadside scope, and design in appealing directly to transportation agencies.

CHAPTER 5

EFFECT OF MAJOR METHODOLOGICAL CHOICES ON PAVEMENT LIFE-CYCLE ASSESSMENT

5.1 Motivation

In this chapter, a series of sensitivity analyses are conducted regarding major methodological choices in a pavement LCA. As a methodology, LCA is governed by a set of rules and preferences that are decided in the goal and scope of the corresponding study. The resulting effect of these choices may or may not have a significant effect on the overall LCA study. Some of these choices refer to general LCA methodological elements such as those related to system boundary, cut-off criteria or data quality. Others choices are specific to the product system, such as the treatment of traffic growth or asphalt binder allocation for pavement LCA. When conducting an LCA, it is important to understand how rules and choices affect the results of the study; in fact, ISO 14040 guidelines require sensitivity analyses as part of the LCA interpretation phase.

In this work, common pavement LCA choices are evaluated with respect to the magnitude of impact that they have on the overall LCA results. The outcome of this work is important for both pavement LCA practitioners and consumers. Sensitivity analyses can distinguish which methodological choices have a significant effect on pavement LCA and which should thus be the subject of more scrutiny and research. By understanding the gravity of different choices, pavement LCA guidelines can further standardize pavement LCA practices by either directly dictating high-impact choices or requiring sensitivity analyses for these choices. If these high-impact choices are not uniform or emphasized across LCA studies, consumers may be presented with misleading information when viewing results from LCA studies with different methodological decisions. In addition, with understanding of the effect of major methodological choices, consumers will be able to make interpretations, decisions or comparisons in a more informed manner by knowing the gravity of the assumptions upon which the results are made. Finally, while sensitivity and uncertainty analyses are related topics, this chapter is specifically focused on sensitivity analyses for LCA, while Chapter 6 addresses uncertainty related to inventory.

5.2 Background

Sensitivity analyses are not an uncommon topic in LCA practice. To the contrary, the ISO 14040 guidelines require sensitivity analyses as part of a larger evaluation of the study results in the LCA interpretation phase (2006a). To establish confidence in the study's findings and conclusions, LCA practitioners are required to conduct a series of checks for completeness, sensitivity, and consistency as described in ISO 14044 (2006b). In addition to the general ISO standards, FHWA's Pavement LCA Framework document also discusses the use of sensitivity analyses (Harvey et al., 2016). A number of instances for which a sensitivity analysis can be applied specifically for the pavement system are mentioned throughout the document, including those related to choices in the goal and scope (e.g., cutoff criteria, system boundaries, allocation procedures, analysis period), inventory data (e.g., inventory sources), pavement performance (e.g., use of metrics, future maintenance and rehabilitation), use-phase (e.g., variables and models, changes in traffic growth and composition over time), EOL (e.g., highly recycled materials), and impact assessment (e.g., normalization reference data, weighting factors). While it is not common practice yet to fully address all evaluation checks of a pavement LCA study, the few studies that do contain sensitivity analyses mainly address issues related to inventory or allocation. It should be noted that studies are excluded in this discussion due to their more comparative nature of, for example, assessing the sensitivity of LCA results to alternative design variations (Meil, 2006) or increasing recycled content (Yang et al. 2015).

Sensitivity analyses related to methodological choices for pavement LCA largely correspond to issues of allocation. Systematic analysis of other issues such as analysis period, system boundaries, and cutoff criteria were not found in the current literature. In pavement LCA, allocation is especially relevant to co-products and EOL recycling. Chen et al. (2010) found significant discrepancies in environmental impacts when using different allocation parameters (i.e., none, mass, economic) to distribute input flows from coal and steel production to fly ash and GGBFS, respectively. A study by Sayagh et al. (2010) found a significant difference of 60% in greenhouse gas impacts over the 30-year lifecycle of a pavement when using 0% and 20% allocation factors for blast furnace slag (BFS) as an aggregate base. Blomberg et al. (2012) evaluated the environmental burdens from producing asphalt binder, finding higher inventory outputs when using mass versus economic allocation. Huang et al. (2013) found that using a mass versus economic allocation for BFS as well as for asphalt binder resulted in higher impacts for a cradle-to-ground pavement reconstruction. The study also found that cradle-to-gate environmental benefits from using recycled material in asphalt mixtures varied widely for different types of impacts depending on the EOL allocation used, reaching 24% for the cut-off method and 70% for substitution. Finally, another study on asphalt binder, Yang et al. (2016), found that environmental impacts were highest when using an allocation based on mass, followed by energy content, volume, and then economic value as the lowest.

Another notable set of literature incorporating sensitivity analyses are related to inventory sources. Meil (2006) collected regional data for the production of asphalt and Portland cement concrete in Canada. The results were performed using different mix designs typical of each region considered, preventing an actual sensitivity analyses of the inventory sources. Huang (2007) performed a LCA for the production and construction of an airport asphalt pavement. A sensitivity check on data sources for asphalt mixing, asphalt binder production, and aggregate production concluded that there were no significant differences in overall results with different data sources. Wang et al. (2012) conducted LCA on the full lifecycle of high and low volume roads. A sensitivity analyses of inventory sources for asphalt binder and Portland cement production showed no significant effect on the overall lifecycle results due to the influence of the use-phase. One more study, Yang et al. (2016), compiled regional processes for the production of various petroleum products, including diesel and asphalt binder, which showed significant differences in environmental impact based on regional representation.

Finally, existing pavement LCA studies also have been seen to conduct sensitivity analyses on pavement-specific items such as those related to hauling distances, use-phase models, and traffic parameters. As the last two parameters tend also to have a high level of uncertainty, many of these studies (Santero & Horvath, 2009; Loijos et al., 2010, Santero et al., 2013) use sensitivity analyses to assess aspects of uncertainty, which is covered in the next chapter. Nonetheless, Meil (2006) did also include a sensitivity analyses of different hauling distances (as well as shoulder design, which is not considered in this discussion). The study found that increases in greenhouse gases were proportional to increases in transportation, and the differences were not significant unless the distances increased dramatically.

Thus, while sensitivity analyses have been conducted for pavement LCA in the past, many of these analyses are limited to allocation and inventory or used to actually assess areas of uncertainties. There exists a gap in quantifying the effect of additional methodological choices such as cutoff criteria and exclusion of infrastructure as well as the effect of electing to use progressive inventory databases or specific impact categories. Furthermore, many existing studies only focus on one or two issues, so that the any significant or insignificant discrepancies found in the sensitivity analyses are isolated. This study considers a range of parameters to which LCA results may be sensitive in a systematic manner that allows for a more complete understanding of which LCA choices and assumptions have significant influence.

5.3 Objective

The objective of the study in this chapter is to conduct a series of sensitivity analyses, some of which have not yet been formally considered in the context of pavement LCA, on various pavement LCA case studies. The parameters assessed for sensitivity include those related to methodological choices typically made in

the goal and scope of an LCA, inventory sources and assumptions, and items chosen for impact assessment. Significant variation in results based on the scenarios considered in the analyses will reveal parameters that have a large impact on the overall LCA results.

5.4 Methodology

A sensitivity analysis is defined by ISO 14040 as "a systematic process for estimating the impacts on the study outcome from choices made regarding methods and data" (2006a). The series of analyses undertaken in this work are feasible due to the LCA software developed in the previous chapter. For each analysis, the relevant parameters are changed in the coding of the software itself or in the software databases as appropriate. The LCA case studies are taken from the case studies presented in the previous chapter as well as additional project from the Illinois Tollway based on contracts between the years 1999–2014. These case studies include projects for both asphalt and Portland cement concrete reconstruction, widening, and new construction as well as resurfacing contracts. A total of eight parameters are considered in this work as listed in Table 5.1. In the preceding section, a detailed description and treatment of each parameter is given preceding its corresponding sensitivity results.

Table 5.1: Summary of Parameters Considered in Sensitivity Analyses

Life-Cycle Phase	Parameter
Goal and scope	Cut-off criteria
	Exclusion of infrastructure
	EOL allocation
	Asphalt binder allocation
	Constant traffic growth
Inventory analysis	Progression inventory databases
	One-way hauling distances
Impact assessment	Primary energy as fuel and material

The main four environmental indicators considered in the sensitivity analyses are those also presented in Chapter 4. They include GWP, PEF, TPE, and a normalized and weighted SS based on the U.S. EPA's TRACI v2.1 method.

5.5 Goal and Scope Choices

5.5.1 Cut-off criteria

The cut-off criteria is defined in ISO 14040 as "specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study" (2006a). In the case studies from Chapter 4, the cut-off criteria for the M&C stage of the a

pavement system was defined as pay items that satisfied at least one criteria of (a) existing in the top 95% of the total cost of all pavement-related items and/or (b) contributing at least 0.5% of the total cost of all pavement-related items. Thus, the criteria was based on cost, rather than amount of material or level of environmental significance. The motivation for using a cut-off criteria is to reduce the number of pay items analyzed to a manageable set due to the significant effort needed to characterize each pay item; however, the chosen method relies on the assumption that an economic cut-off criteria could be used for an environmental analysis because the two components are related.

To investigate the sensitivity of the cut-off criteria, the relationships between economic and environmental contributions for pay items in eight pavement projects are examined. The environmental impacts of systematically excluding pay items one at a time from the original set of pay items were determined. The pay items are removed in order of lowest to highest economic contribution. The three graphs in Figure 5.1 demonstrate the types of behavior that can be expected. If the curves are closer to the equality line (a), the economic and environmental impacts are proportional; thus, including more of any pay item is beneficial. If the curves are convex (b), the low cost items contribute to higher impact items; thus, including more of the supporting or lower costing pay items is important to capturing environmental impacts. Finally, if the curves are concave (c), the higher cost items contribute to higher environmental impacts; thus, including the top cost items are important.

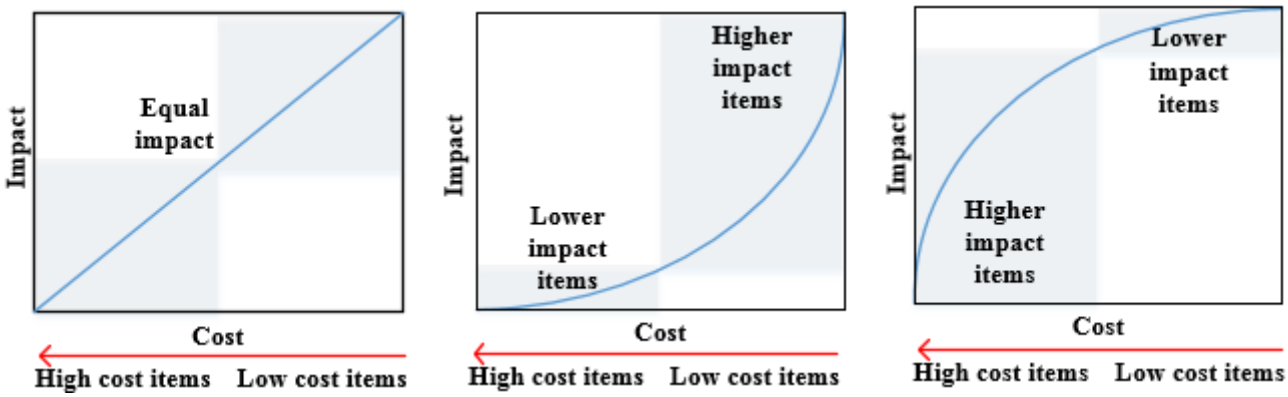


Figure 5.1: Explanation of cut-off criteria significance for curves of (a) equality, (b) convex, and (c) concave.

From the graphs in Figure 5.2, it can been seen that the curves all fall above the equality line (i.e. concave), and they are relatively close to the equality line, implying that cost and environmental impact are related. The curves are slightly concave, implying that it is more important to include the top cost pay items. This

is the case in the 95%/0.5% cut-off criterion, which is appropriate because it ensures that the most items contributed the most to the total pavement-related cost are considered in the LCA.

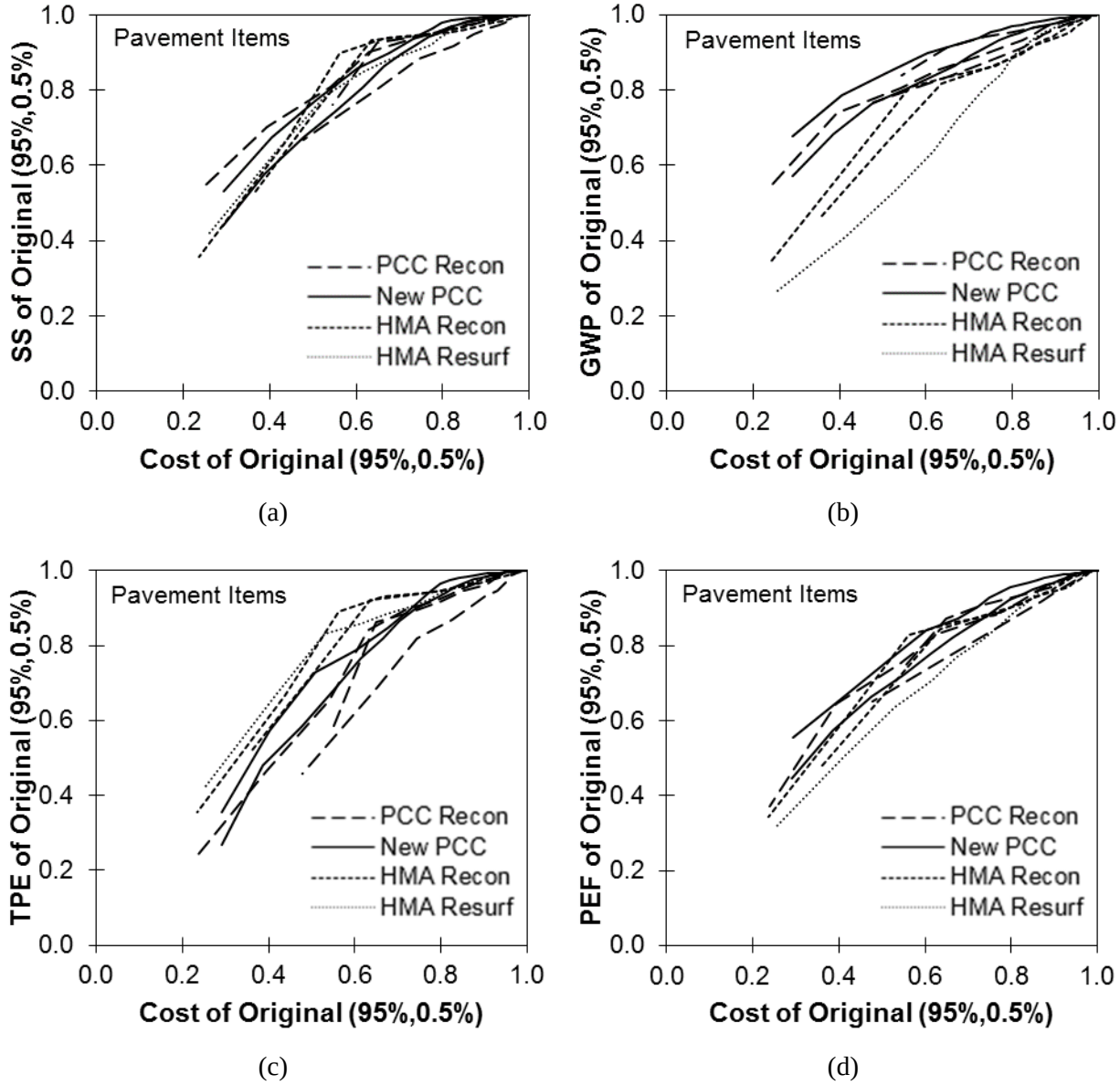
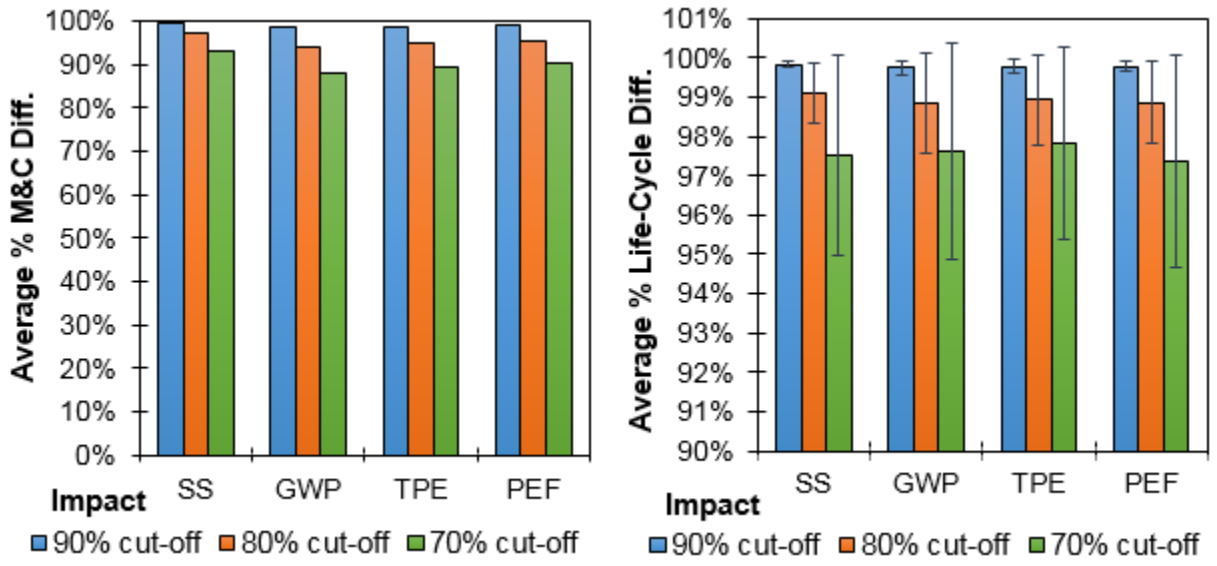


Figure 5.2: M&C pay item cut-off sensitivity for case studies for (a) SS, (b) GWP, (c) TPE, and (d) PEF.

Having established that including the top cost pay items is important, the sensitivity of how much of the top items to include can also be investigated. For all projects, the reduction in impacts when considering 90%, 80%, and 70% of the top cost pay items instead of 95% can be seen in Figure 5.3 (a). When including M&C pay items falling within the top 70% of the total cost of the contract, the corresponding loss in environmental impacts from using the top 95% cut-off criteria is in the range of 7%-

12% (i.e., less than the expected 15%). This supports the conclusion made previously that the pay items contributing to the greatest environmental impacts are also those that contribute to the greatest cost. However, a loss of 12% (or even 5% from the 90% cut-off criteria) in the environmental impacts is quite high for the M&C stage, so it is not recommended to lower the cut-off criteria. This suggestion may be reconsidered when looking at the effect of changing the cut-off criteria on the entire life cycle in Figure 5.3 (b). In this case, the excluded impacts when using a 70% cut-off constitutes approximately 2%-3% of the total life-cycle impacts. Thus, when focusing on the entire life cycle, it may be possible to lower the cut-off criteria to reduce the time and information needed for the LCA without compromising the evaluation of environmental impacts.



(a) (b)

Figure 5.3: Average percent difference in impacts for different cut-off criteria for (a) M&C stage and (b) the entire life-cycle.

5.5.2 Exclusion of infrastructure

A methodological choice is often made in pavement LCA to exclude impacts from infrastructure or capital goods. This includes, for example, the manufacturing and maintaining a bulldozer; whereas, the LCA study only considers the impacts from using and mobilizing the equipment. However, in order to determine whether or not this exclusion is suitable, a sensitivity analysis is performed. In this analysis, only the use and EOL stages were considered due to constraints in time and resources. Infrastructure impacts were only included for vehicle processes (i.e., off-road equipment, on-road autos and trucks), which includes manufacturing and maintenance of the vehicle. Infrastructure impacts for all other processes would require

significant additional information (e.g., building and maintenance of facility and all equipment used in the process) that was not available at the time. Infrastructure processes included the manufacture of the vehicle as well as maintenance of the vehicle as distributed over the life of the vehicle. The corresponding impacts were taken directly from US-EI 2.2 for a typical passenger car or large truck; thus, infrastructure is considered independently from the pavement and does not include effects from deteriorating pavement conditions over time. Four diverse projects[13] were analyzed with and without the vehicle-related infrastructure impacts. As seen in Figure 5.4, the effect of considering infrastructure in the LCA is significant. The average percentage contributions of infrastructure when included in the use stage are 65% for SS, 20% for GWP, 15% for TPE, and 20% for PEF, while those for the EOL stage are 48%, 17%, 28%, and 28%, respectively.

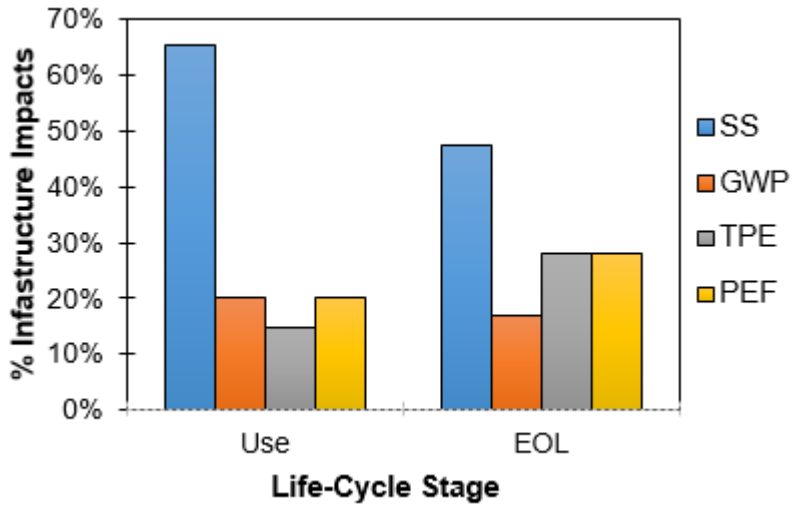


Figure 5.4: Average contribution of infrastructure impacts for select projects for the use and EOL stages.

When viewing the contribution of infrastructure impacts on a per-process basis, it is clear that each process' impact is affected differently. In Figure 5.5, the infrastructure impacts for vehicles as used in the sensitivity analysis are shown alongside those for other processes directly taken from US-EI 2.2. The contribution of infrastructure to passenger car impacts is the highest at approximately 20% for fuel-related impacts and over 65% for SS. Infrastructure impacts for haul truck and aggregate production are also high, followed by asphalt paver, and then Portland cement and asphalt binder production. Overall, the SS contributions from infrastructure are highest out of all impacts, as they reflect effects on human health, ecological systems, and fuel.

[13] The four projects included a PCC reconstruction (5228), a HMA reconstruction (5542), a new PCC construction (7710), and a HMA resurfacing project (8101).

Thus, the sensitivity analysis shows that emissions from infrastructure are not negligible in the LCA (i.e., they are much greater than 1%), potentially conflicting with the choice to exclude these impacts in the Goal and Scope. Thus, it may be suggested in future studies to show results both with and without infrastructure emissions.

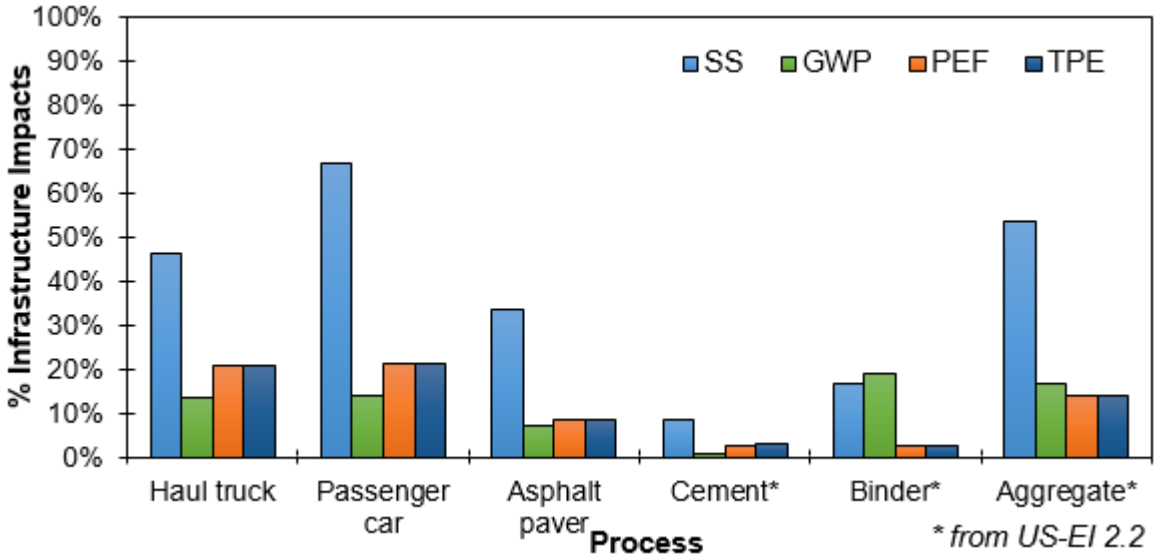


Figure 5.5: Contribution of infrastructure to various processes for each environmental indicator.

5.5.3 EOL allocation

Allocation deals with the "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", as defined in ISO 14040:2006. While the sensitivity effect of allocation has been addressed by other pavement-related LCA studies in a more limited fashion (e.g., Chen et al., 2010; Sayagh et al., 2010; Blomberg et al., 2012; Huang et al., 2013; Yang, 2014), EOL allocation and asphalt binder allocation are discussed in this work in the context of the entire pavement lifecycle.

A cut-off allocation was chosen to address EOL burdens in the larger work. Specifying an allocation procedure to use at EOL is especially important for road systems because a significant amount of construction material (e.g. AC and PCC) may be recycled at the end of the system's life. Depending on the allocation choice, the benefits from using the subsequent recycled materials may be attributed to the original system or the future system or split between the two systems. A number of allocation methods have been established to attribute environmental impacts between chained product systems (e.g. Figure 5.6), where a portion of the product in system 1 is incorporated into system 2. In this sensitivity analysis, the methodological choice of using the cut-off method versus the substitution method for allocation will be

evaluated as they pertain to asphalt concrete and PCC pavement at EOL. Other recyclable materials in the pavement project system such steel and aggregate are not considered in this analysis.

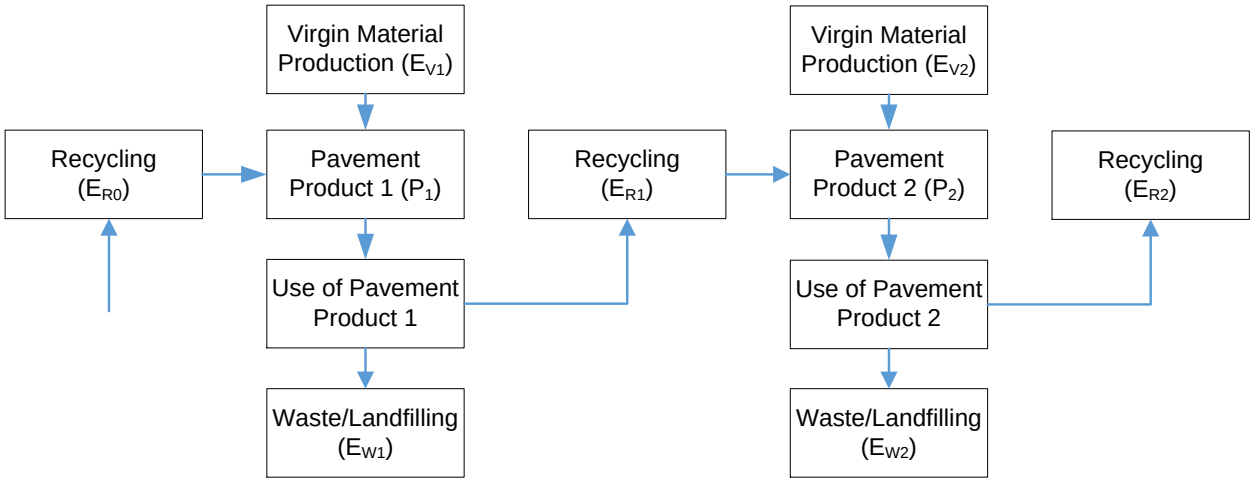


Figure 5.6: Chained product systems: Pavement Product 1 and Pavement Product 2.

The cut-off method, often used in pavement LCA studies, does not assume anything about the recyclability of the original system at EOL, and thus assigns environmental impacts to the system directly responsible for producing or processing the material (Nicholson et al., 2009). Another popular allocation method is substitution, which treats the recycled material used in the future system as a substitute for virgin material and thus assigns burdens proportional to any "lost" material not continuing in the chain of product systems (Nicholson et al., 2009). The latter method is commonly employed for metals because these items are assumed to retain their original properties and value when recycled. The two methods are defined explicitly in Equations (5.1) through (5.4), styled after Huang et al. (2013) and Nicholson et al. (2009). Thus, the allocations affects not only the EOL stage, but also the M&C and maintenance and rehabilitation (M&R) stages.

Cut-off Method

$$E_{P1} = X_1 E_{V1} + (1 - X_1) E_{R0} + L_1 E_{W1} \quad (5.1)$$

$$E_{P2} = X_2 E_{V2} + (1 - X_2) E_{R1} + L_2 E_{W2} \quad (5.2)$$

Substitution Method

$$E_{P1} = (1 - L_1) E_{R1} + L_1 E_{V1} + L_1 E_{W1} \quad (5.3)$$

$$E_{P2} = (1 - L_2) E_{R2} + L_2 E_{V2} + L_2 E_{W2} \quad (5.4)$$

Where:

X_1, X_2 are the percentages of virgin material used in Products 1 and 2;

L_1, L_2 are the percentages of Products 1 and 2 landfilled;

E_{P1}, E_{P2} are the environmental impacts of Products 1 and 2 (including construction, use, etc. to EOL removal and transportation to next site or facility) ;

E_{V1}, E_{V2} are the environmental impacts of producing virgin materials for Products 1 and 2;

E_{R0}, E_{R1}, E_{R2} are the environmental impacts of processing recycled material from Products 0, 1, and 2 for the next system; and

E_{W1}, E_{W2} are the environmental impacts of landfilling materials for Products 1 and 2.

To investigate the effect of using a substitution versus cut-off allocation, three pavement projects have been selected: I-07-5228 (PCC reconstruction and widening from 2007), I-08-5542 (full-depth HMA reconstruction and widening from 2008), and I-13-4133 (composite PCC reconstruction and widening from 2013). Two scenarios with 5% and 50% landfilling were considered for both asphalt and concrete pavement as seen in Table 5.2. Any material reused at EOL was assumed to have negligible processing (E_R) for the next system.

Table 5.2: EOL Allocation Sensitivity Scenarios

Pavement Type	% Landfill	% Recycling	% Reuse
Asphalt	5	95	0
	50	50	0
Concrete	5	45	50
	50	22.5	27.5

These projects were selected to cover both traditional asphalt and concrete pavement reconstruction as well as a newer composite concrete pavement reconstruction that utilized more recycled material. Traffic-related impacts (i.e. use-phase and work zone related emissions) were not considered in the sensitivity analysis to better see the differences in material production and EOL. Thus, it should be noted that any differences seen are relatively smaller when considering the entire life-cycle of the pavement.

From the analysis in Figure 5.7, it is clear that employing the substitution rather than cut-off method reduces the total impacts of the original pavement system producing the material significantly for all impacts. This is reasonable because the substitution method shares the credit of the recycled material among the producer and user of the recycled material, while the cut-off method gives the credit to the user of the recycled material. The reductions for the original 5% landfilling varies from 39%-76%, which implies that the choice of allocation for EOL is a methodological choice with significant influence. If the landfill rate is increased to 50%, the reductions decrease to 20%-40%. In this scenario, the pavement system incurs the environmental burdens for producing the 50% of pavement that is landfilled. These differences are still

notable, and for a product system with a high recycling rate in the United States, the choice of allocation for EOL will be important.

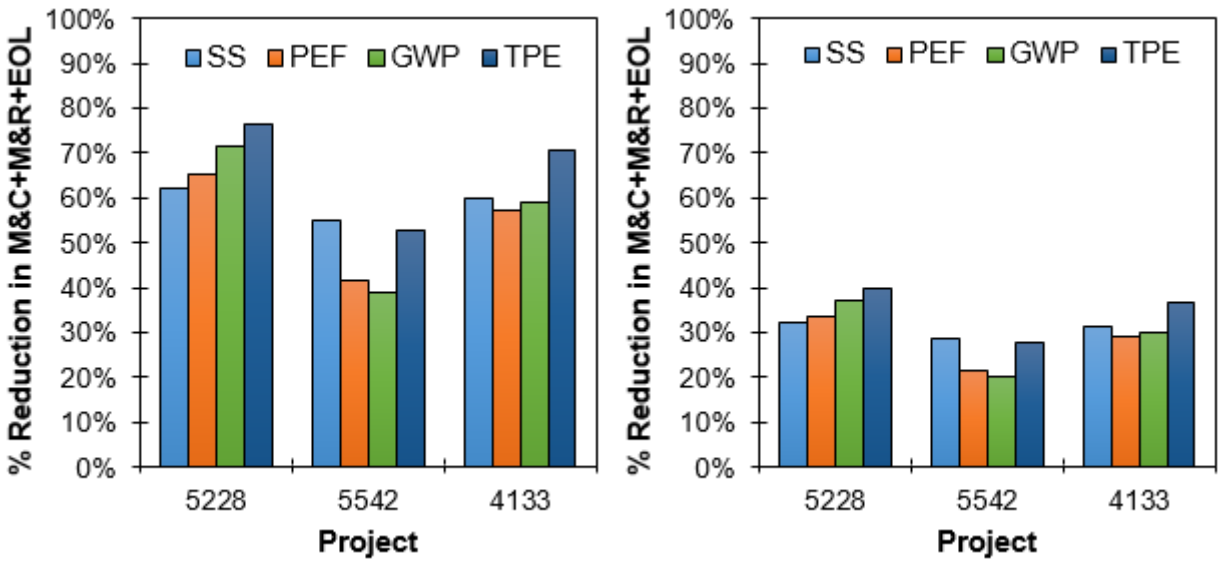


Figure 5.7: Effect of using a substitution versus cut-off EOL allocation scenario on impacts for a (a) 5% landfill rate and a (b) 50% landfill rate for select projects on the M&C, M&R, and EOL stages.

A few remarks can be made regarding the projects themselves. The 4133 project includes a composite PCC pavement with more recycled material than the 5228 PCC project. A reason that the reduction between the cut-off and substitution method is slightly lower for 4133 than for 5228 is because the burdens from producing PCC in 4133 is lower than for 5228, so shifting that burden to a different system is more significant for the 5228 project. The 5542 asphalt pavement project is lower for the 5% landfilling scenario but higher for the 50% landfilling scenario among all three projects. This indicates that the pavement material landfilled incurs relatively less impacts to produce than for the other projects.

5.5.4 Asphalt binder allocation

An economic allocation based on the relative market value of asphalt binder in Illinois was chosen to assign a proportion of refinery processes to asphalt binder. As recommended by ISO 14044, the sensitivity of allocation methods can be checked in the LCA interpretation (2006b). In the case of asphalt binder, the allocation method was obtained from a study (Yang, 2014) that also includes allocation factors using mass and energy content. In general, the method for calculating the refining allocation from Yang (2014) is described in Equations (5.5) to (5.7) below, where p is a petroleum product in the set of all petroleum products P outputted from the refinery, M_p is the total mass yield of petroleum product p from the refinery,

and X_p is the total allocation parameter yield of petroleum product p from the refinery. The factor is calculated with respect to mass yield because the original refinery processes are given per short ton of product. For example, if the allocation is by market value, X_p then refers to the total economic yield of petroleum product p in the refinery.

$$Allocation\ coefficient = \frac{X_{asphalt} \times M_{asphalt}}{\sum_{p \in P} X_p \times M_p} \quad (5.5)$$

$$Mass\ residue\ yield = \frac{M_{asphalt}}{\sum_{p \in P} M_p} \quad (5.6)$$

$$Allocation\ factor = \frac{Allocation\ coefficient}{Mass\ residue\ yield} \times 100 \quad (5.7)$$

Using the 2012 – 2015 values for the U.S. Midwest region (Petroleum Administration for Defense District 2), the allocation factors from Yang (2014) using energy content, mass, and volume are shown in Table 5.3.

Table 5.3: Allocation Factors for Asphalt Binder

Allocation Type	Factor
Economic	41.9%
Energy Content	88.9%
Mass	100.0%
Volume	75.1%

Using the different allocation methods, eight pavement projects were assessed. From the results in Figure 5.8, the difference in life-cycle impacts due to different asphalt binder allocation is small and on average less than 2%. Using an allocation by mass has the largest impacts followed by that by energy and then by volume. In Figure 5.9, the difference on the results of just the M&C and M&R stages are higher and on average around 6%, which is notable. Interestingly, the difference in results is only apparent for GWP, TPE, and PEF; SS is not affected. This implies that SS is influenced largely by another processes in the production of asphalt binder (i.e., crude extraction), so that any changes in impacts from refining are not significant.

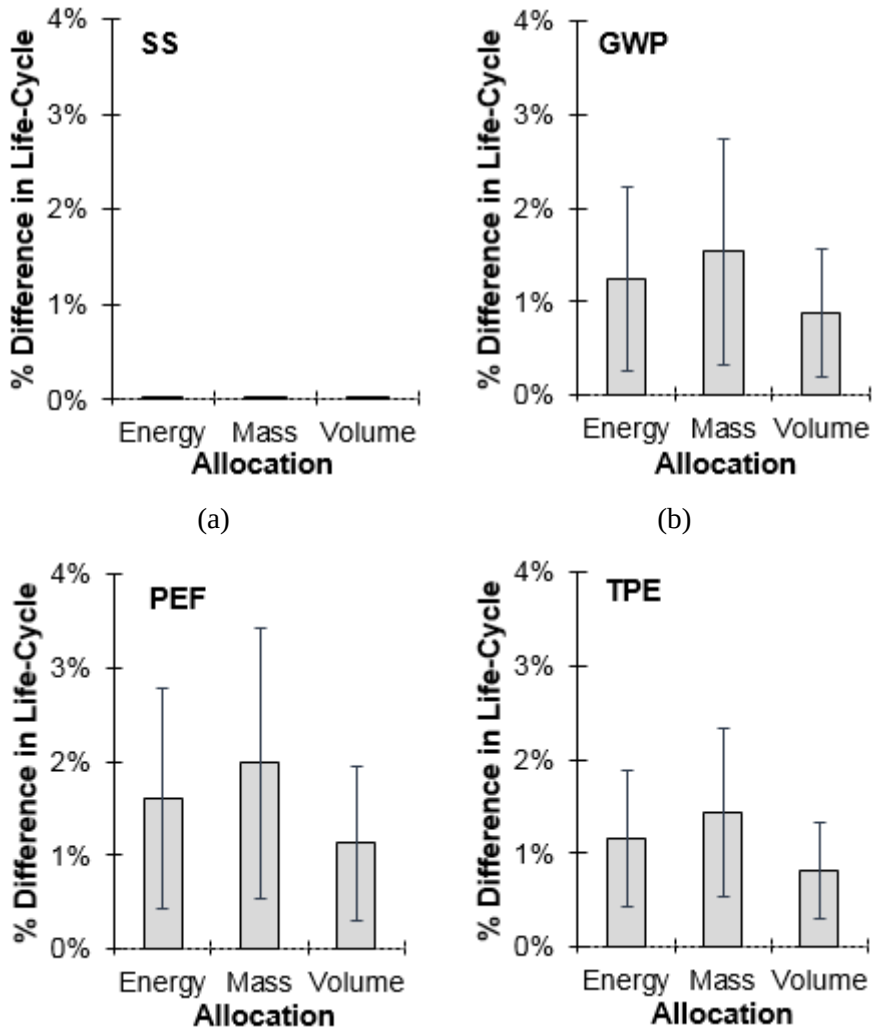


Figure 5.8: Differences in asphalt binder allocation for each projects w.r.t. all life-cycle stages for (a) SS, (b) GWP, (c) PEF, and (d) TPE.

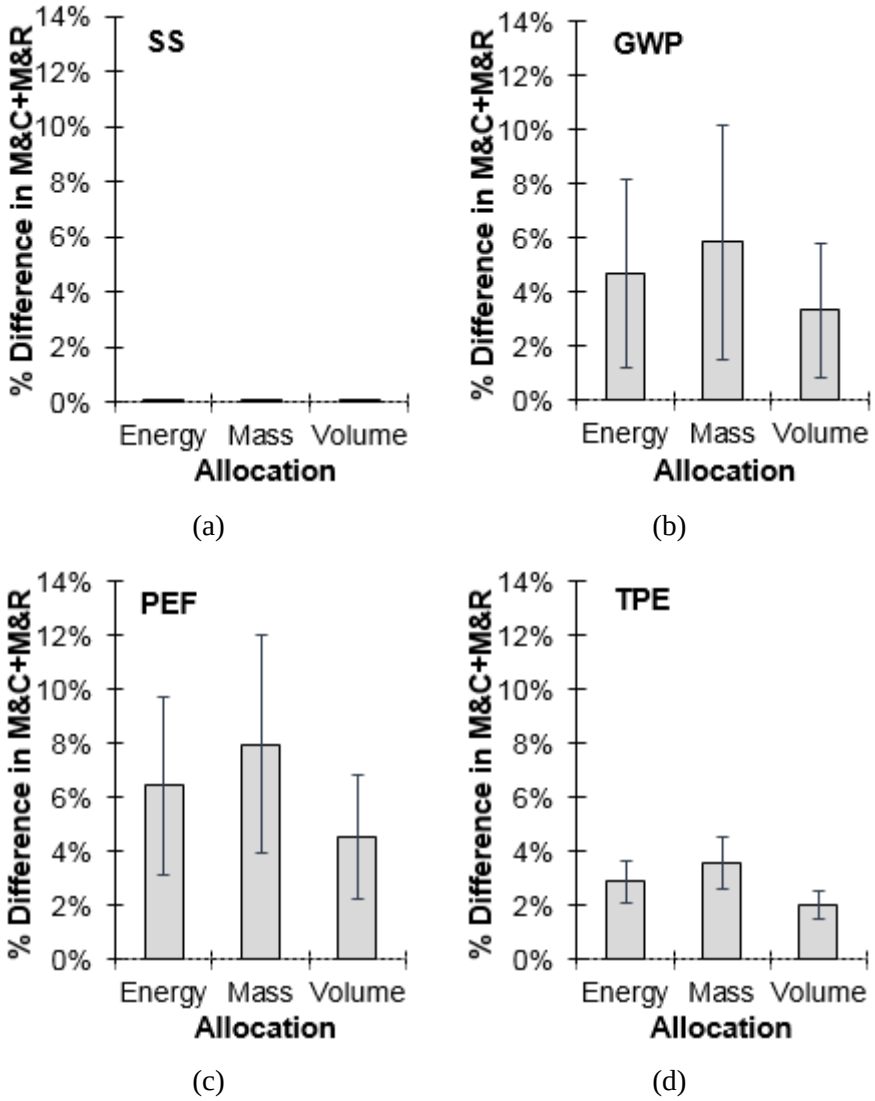


Figure 5.9: Differences in asphalt binder allocation for each projects w.r.t. only the M&C and M&R stages for (a) SS, (b) GWP, (c) PEF, and (d) TPE.

5.5.5 Constant traffic growth

The next parameter with known uncertainty that may affect LCA results is traffic growth over time. This parameter is significant for the use-phase and has been observed to be unstable over time. In the LCA analyses in Chapter 4, a constant rate is assumed for the duration of the pavement's life cycle. This constant rate is determined using historical and predicted Illinois Tollway traffic data for the appropriate toll road; however, from the same traffic information, it was observed that the traffic growth rate undulates from year to year (sometimes even becoming negative one year and positive the next). To determine the effect of

considering non-constant growth rates, an uncertainty analysis was run using the 5541 project involving a full-depth asphalt pavement reconstruction over a 75-year analysis period.

As shown in Figure 5.10, random traffic growth rates were generated for five samples using a random number generator set between rates of -2.5% and 5.5%. The original growth rate for this project was 1.47% and the mean growth rates for the five randomly generated traffic progressions were between 1.25% - 1.93%.

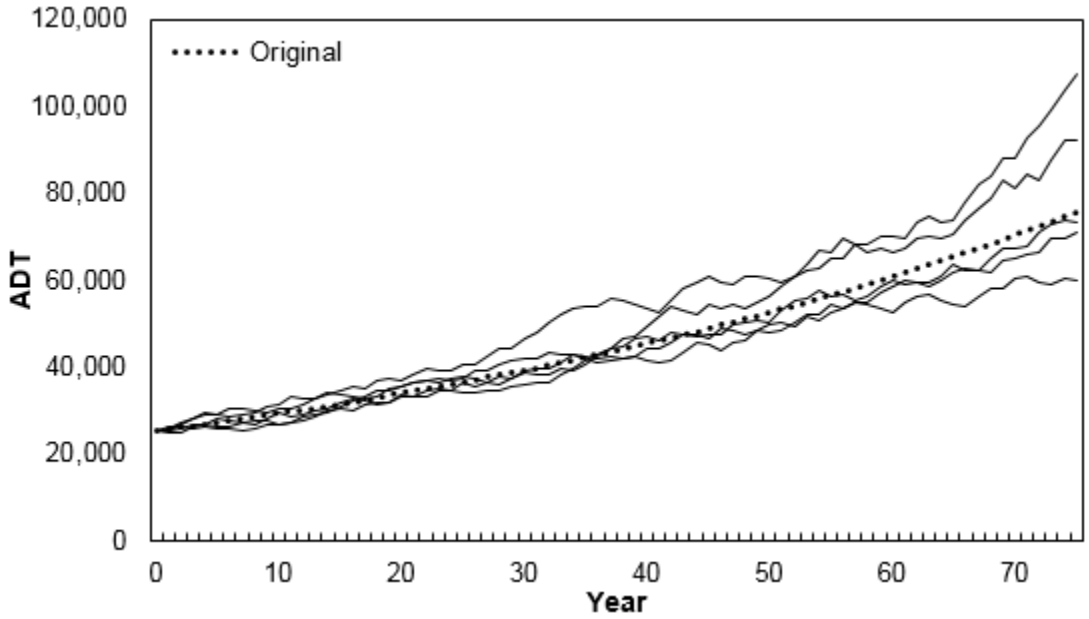


Figure 5.10: Random traffic growth progressions for five trials for project 5541 over 75 years.

For each of the random traffic progressions in Figure 5.10, the life-cycle impacts were calculated and analyzed to produce the distribution shown in Figure 5.11. Using the random traffic growths, approximately 68% or one standard deviation of the impacts would stay within +/-20% of the original results. This variation is quite significant and future work could include more simulations to provide a more representative distribution to describe the range of results possible.

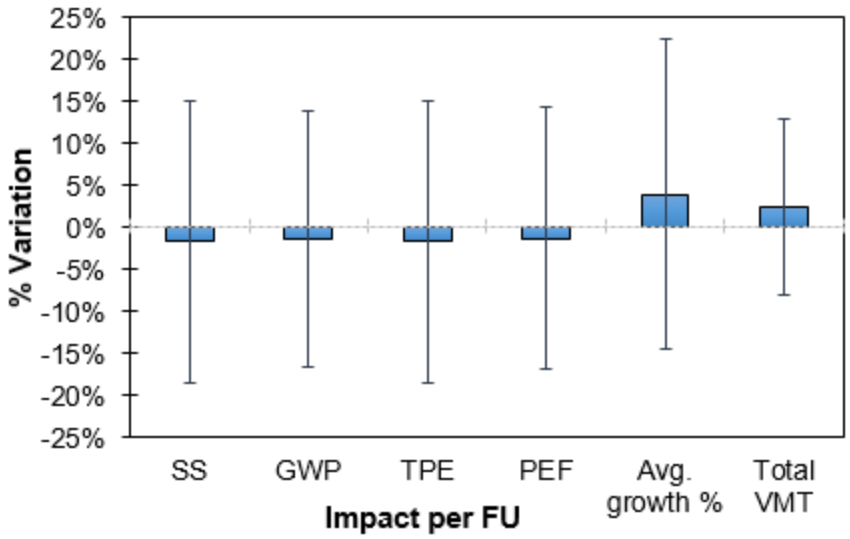


Figure 5.11: Percent variation in impacts per functional unit (FU) for project 5541 using five randomly generated traffic growth progressions.

5.6 Inventory Analysis Choices

Dynamic life-cycle impact assessment (LCIA) databases were implemented in the LCA study in Chapter 4 to better represent the temporal characteristics of the processes considered. A "baseline" and "current" LCIA database was considered for material production, hauling, and plant operations based primary on the different electricity mixes used in Illinois in 2000 and 2009 (Al-Qadi et al., 2015). In addition, the equipment database included simulations from EPA NONROAD2008 that estimated fuel efficiency and combustion emissions for machines used in Cook County, Illinois from 1999 to 2015. To determine the effect of using these different databases, a sensitivity analysis was conducted. The eight pavement projects were analyzed using various databases.

5.6.1 Progressive inventory database – materials

The effect of using the baseline versus current LCIA database was first examined. Only M&C pay items were considered because all of the materials used in these pay items had unit processes existing in both the baseline and current databases. The original projects were analyzed using the baseline LCIA database, and the percentage reductions from substituting the current LCIA database are shown in Figure 5.12.

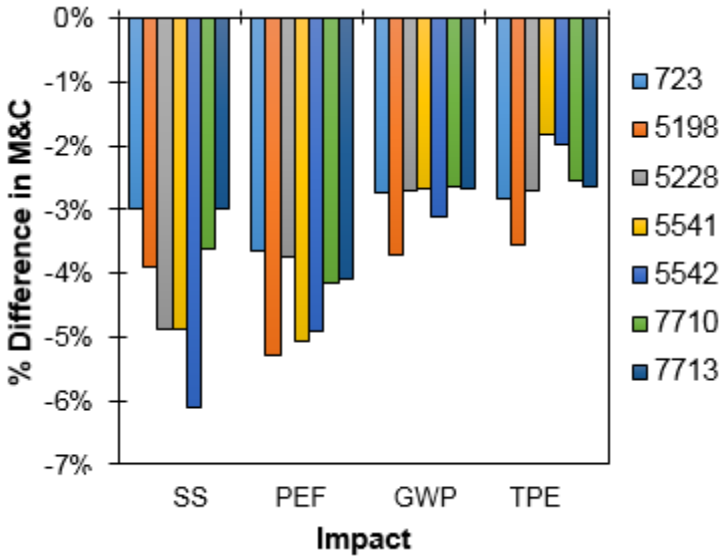


Figure 5.12: Percent difference from original projects impacts using the current LCIA databases for the M&C stage.

The reduction in impacts when using the current LCIA database instead of the baseline LCIA database for the projects range from 1.8%-6.1%. The average reductions (and standard deviations) are 4.2% (1.1%) for SS, 4.4% (0.7%) for PEF, 2.9% (0.4%) for GWP, and 2.6% (0.6%) for TPE. In general, the greatest reduction in impacts occurs with SS, then PEF, GWP, and finally TPE. The difference between the baseline and current databases are mostly due to differences in electricity generation[14]. It is reasonable that the SS is affected the most because the other impacts are fuel-based impacts and thus would be less affected by changes in electricity generation. A reduction of 6% is significant in the M&C stage; however, when taken into account over the entire life-cycle, the difference may be smaller.

5.6.2 Progressive inventory database – equipment

The effect of considering yearly equipment was also investigated with respect to the same eight projects. The construction years of the projects span from 1999 to 2008, and M&C pay items were assessed using equipment modeled for the initial construction year. Equipment used in the M&R stage were also modeled based on the year at which rehabilitation was done until the year 2015, after which the 2015 database was exclusively used due to the limited database. Due to the long analysis periods (44 to 78 years), the majority of M&R activities were assessed using 2015 equipment; thus, only M&C pay items are assessed in this sensitivity analysis.

[14] In some cases, a blanket 2% reduction in environmental impacts was modeled for the current database when electricity was not a main process within the unit process. In this case, all impacts would be affected equally.

The original project results for the M&C stage were compared with new results when using exclusively the 2015 equipment database as shown in Figure 5.13, where the projects have been order by construction year. In addition to the four main impacts SS, PEF, GWP, and TPE, respiratory effects (REP) has also been added.

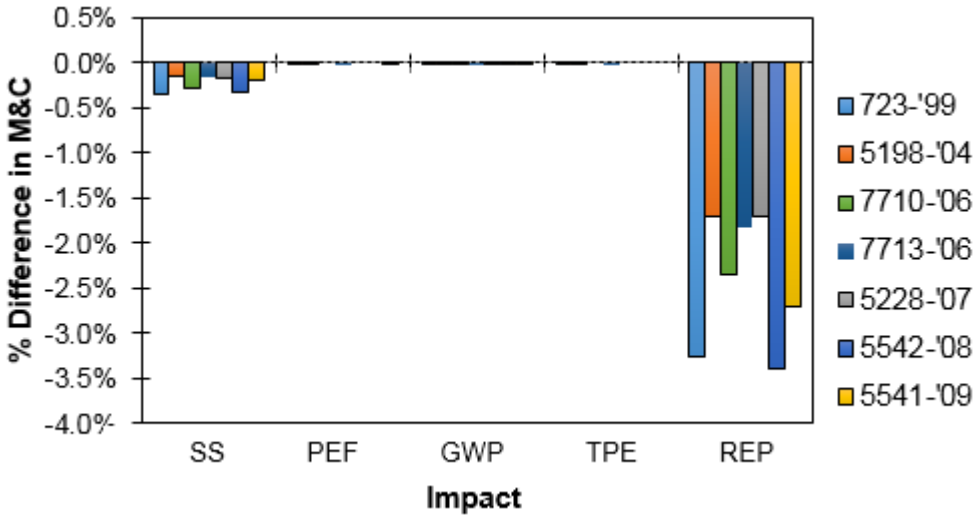


Figure 5.13: Percent difference from original progressive projects impacts when using the 2015 equipment database for the M&C stage.

The reduction in impacts vary from 0.0%-3.4%, with only SS and REP having noticeable reductions. The average reductions (and standard deviations) are 0.2% (0.1%) for SS, 2.5% (0.7%) for REP, and 0.0% for all other impacts. The fuel-related impacts (i.e. PEF, GWP, and TPE) do not show discernable differences, implying that the modeled fuel efficiency (gallon/hour) of the equipment are not improving much over time. Instead, SS and REP are reduced over time, due to nonroad diesel emissions standards that restrict the following emission: carbon monoxide (CO), hydrocarbons (HC), non-methane hydrocarbons (NMHC), nitrogen oxides (NO_x), and particulate matter (PM). Of these emissions, all, except HC and NMHC directly impact REP.

There is no discernable trend relating construction year and magnitude of impact reduction in Figure 5.13 because each of the projects have different equipment needs and intensities as shown in Figure 5.14. The contribution of equipment usage to the overall impacts for M&C pay items range from 0.6%-10.2%, which limits the effect that a more precise equipment database may have on the overall results.

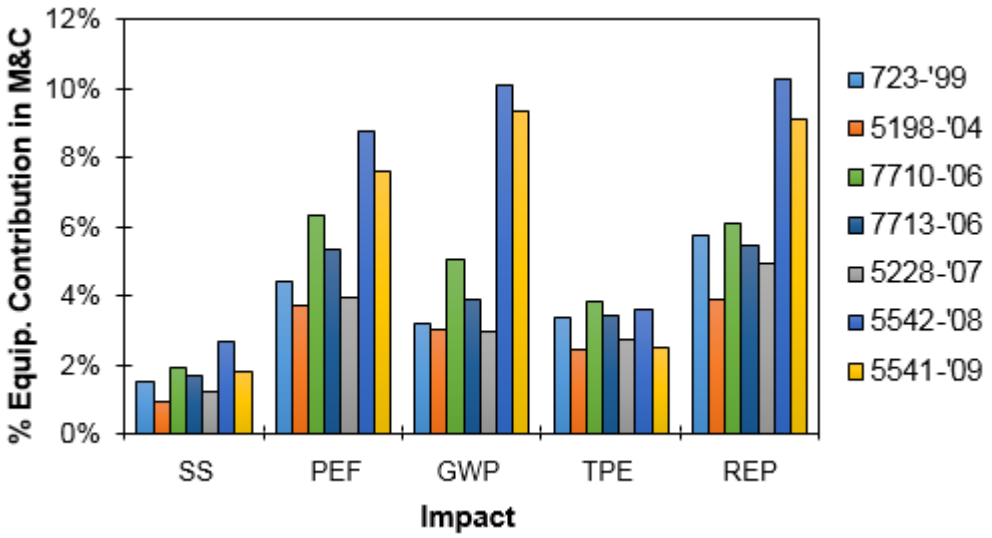


Figure 5.14: Percent contribution of equipment processes to various impacts in the original projects for the M&C stage.

5.6.3 Progressive inventory database – technology

While the LCA analyses in Chapter 4 utilized progressive LCIA databases, these databases are discrete and limited. There are only two material LCIA databases representing information circa 2000 and 2015, as well as databases for equipment from 1999-2015. In both of those database sets, the impacts were seen to improve over time due to better technology and stricter regulations. In addition, increasingly regulations for vehicle emissions and larger proportions of electric and hybrid technologies in the vehicle mix over time would also cause a systematic reduction in environmental impacts over time for vehicles. In order to determine the effect of a continuous improvement in technology over time, a constant percentage improvement per year was considered for processes related to material production, equipment usage, and vehicle emissions and energy consumption. The full-depth asphalt pavement reconstruction (5541) was chosen for this analysis, and its life-cycle was analyzed five times with a constant annual rate of improvement in all unit processes of 0.2%, 0.6%, 1.0%, 2.0%, and 4.0%.

As seen in Figure 5.15, the reduction in life-cycle impacts is exponential with increasing rates of annual improvement. A 0.2% annual improvement results in an average reduction of 5% in impacts, while a 4.0% annual yields a reduction of over 50%. The majority of the reduction in impacts is due to the use-phase; at the end of the 75-year analysis period, vehicle impacts are only 4% to 86% of the original impact at year 0 for a 0.2% to 4.0% annual improvement. While it is difficult to determine the annual improvement rates appropriate for each process, it may be beneficial to incorporate improvements for processes expected to have continuous reductions in environmental impacts (e.g., vehicles versus an aggregate quarry).

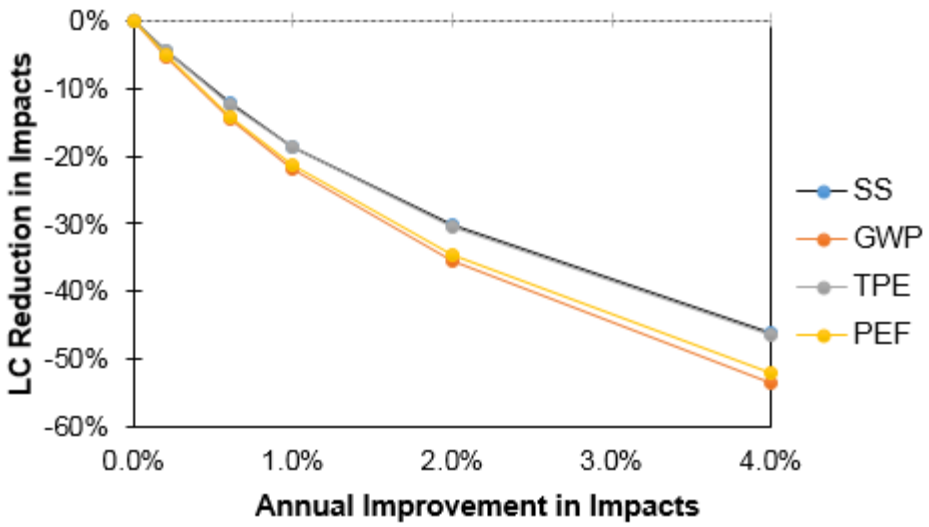


Figure 5.15: Effects of improved technology at various rates on environmental impacts for project 5541.

5.6.4 Hauling distances

Hauling distances of materials and equipment can vary widely across projects and even among mixes, materials, and equipment. For example, less common or specialized material or equipment may need to be hauled from greater distances as opposed to more common, local materials and equipment. The sensitivity of hauling distances for various purposes (i.e. to-plant, to-site, off-site) is analyzed in this analysis. The M&C pay items for all eight pavement projects are considered in the analysis for simplicity, though it is expected that the analysis outcome will be similar also for M&R and EOL pay items.

The hauling distances for each purpose are multiplied by a factor of 0.5 and 2.0, and the effects of doing so on the transportation intensity are calculated. Transportation intensity is a local indicator measured in short-ton-miles representing the total amount and transportation of raw material-to-plant, plant material-to-site, raw material-to-site, and material off-site. From Figure 5.16, the average of the transportation intensity over all projects is shown along with standard deviations. For these projects, the transportation purposes most affected are in order of greatest to least (1) raw material-to-plant, (2) raw material-to/off-site, (3) plant-to-site, and (4) equipment-to-site. The standard deviation for raw material-to-plant and raw material-to/off-site are the highest, as these materials can come from short or long distances. The plant-to-site distances are more consistent, as plants are often located within ten miles of the construction site. As opposed to the other distances which were obtained from actual project information, the equipment mobilization distances were estimated based on how common the equipment was perceived to be. Thus, the standard deviation for mobilization is very small.

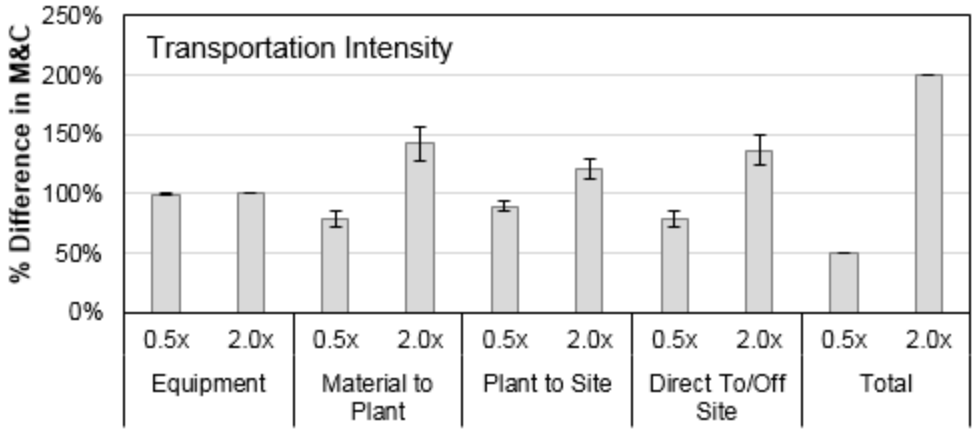


Figure 5.16: Average effects of halving and doubling hauling distance on transportation intensity (short-ton-miles) in the M&C stage.

The effects of halving or doubling hauling distances on the total M&C pay item impacts follow a similar trend for each environmental impact, as shown in Figure 5.17. The percentage differences from modifying the total distances by 0.5 or 2.0 in order of least to greatest effect are 98.9%-102.5% for SS, 97.6%-104.6% for TPE, 95.6%-108.8% for PEF, and 95.5%-109.0% for GWP. As expected, the impacts that are affected the most are those related directly to fuel consumption: GWP and PEF. Thus, the effect of reducing hauling distances by half ranges from 1.1%-4.5%, which implies that efforts to lower hauling may be a lesser priority for the M&C stage. Overall, it should be noted that the life-cycle impact of different hauling distances will then have a much smaller impact.

Finally, it should be noted that the transportation distances were considered to be one-way trips in this study. If empty return trips are considered, the distances would essentially be doubled[15] and, as seen from this sensitivity analysis, the total impacts from M&C pay items could increase by up to 10% for fuel-related impact.

[15] The distances would be doubled, but the return trip would be empty, causing the return impacts to decrease due to the reduced weight.

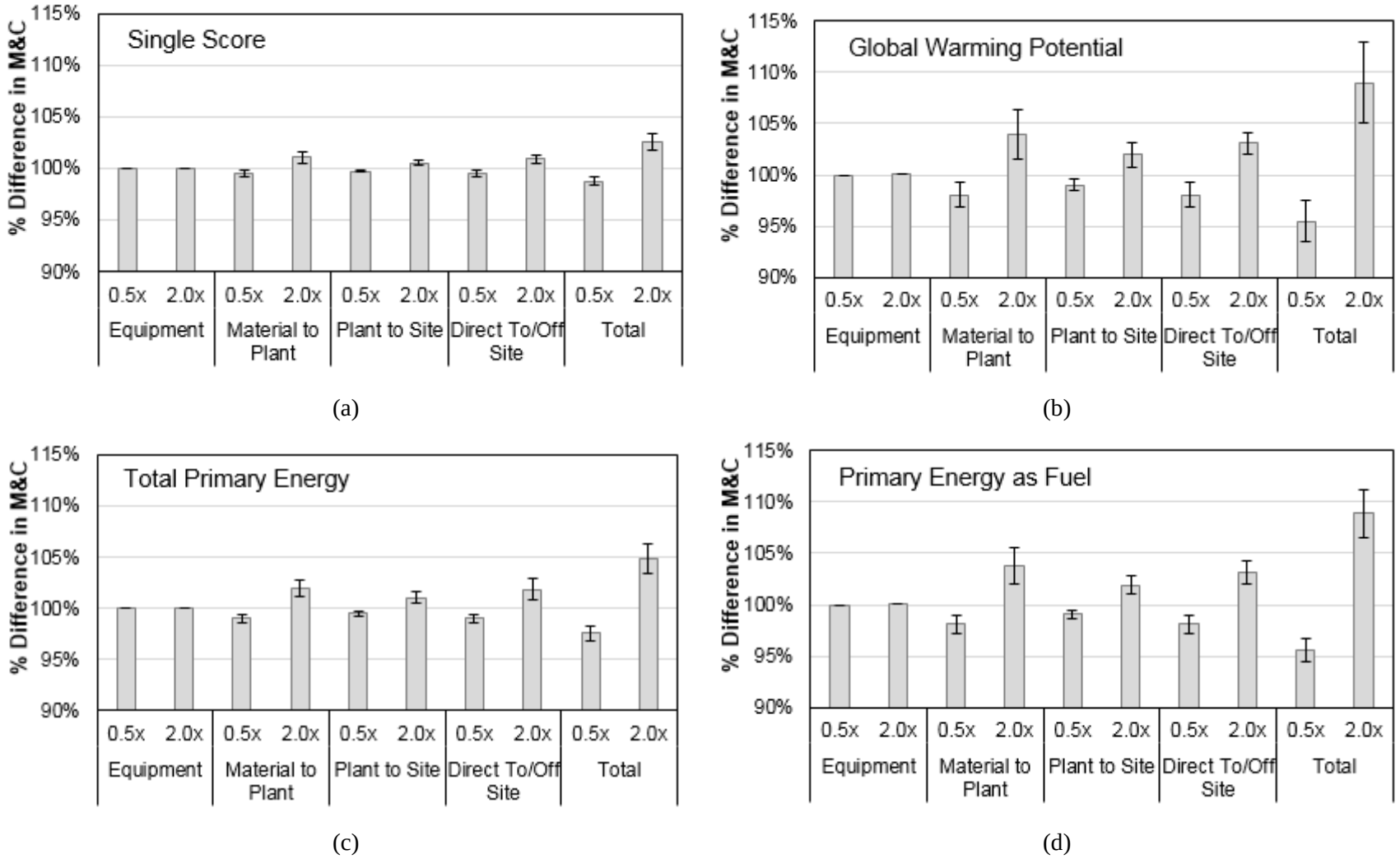


Figure 5.17: Percent difference in M&C impacts from halving and doubling hauling distances for (a) SS, (b) GWP, (c) TPE, and (d) PEF.

5.7 Impact Assessment Choices

5.7.1 Primary energy as an impact category

Sensitivity analysis can also be applied to methodological choices beyond the inventory, such as choices made about impact assessment. The FHWA pavement LCA framework suggests to report a breakdown of energy types, including energy as fuel and energy as material (Harvey et al., 2016). This issue is especially relevant for pavement because energy as material (i.e. TPE) includes feedstock energy from asphalt binder. Arguments have been presented in support of as well as against the exclusion of feedstock energy due to its influence on the energy consumption of pavement systems (Santero, 2009). In order to see the effect of including or excluding energy as material in this LCA study, the primary energy consumption from the eight pavement projects are plotted in Figure 5.18 for the entire lifecycle.

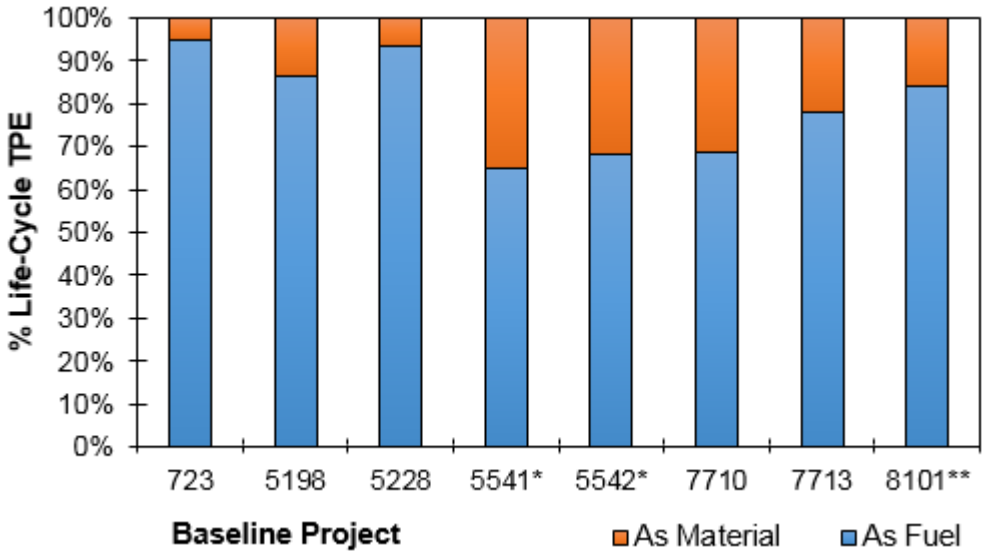


*Figure 5.18: Percentage of TPE as fuel and material for each projects, where * indicates an HMA reconstruction and ** a resurfacing project.*

The percentages of TPE from material range from 5.1%- 35.2%, with an average of 20.2% and a standard deviation of 11.8%. The projects with the highest primary energy as material (PEM) percentages are 5541 and 5542, which are full-depth asphalt reconstruction projects, which have considerable asphalt binder in both the mainline and shoulders. Next, 7710 and 7713 also have relatively high PEM; these are new PCC construction projects with HMA shoulders and have lower traffic volumes and thus a higher overall life-cycle impact from materials. Finally, 8101 has a higher PEM percentage because it is a HMA

resurfacing and patching project. With the significant and varying contribution of PEM to TPE as shown in this sensitivity analysis, it is important to report TPE but also distinguish between PEM and PEF.

5.8 Summary

The main objective of the work presented in this chapter was to determine the significance of various methodological choices made in a pavement LCA study. These choices were related to parameters decided as part of the goal and scope, inventory analysis, and impact assessment of the LCA. Sensitivity analyses were conducted for each parameter on one or more actual projects representing Illinois Tollway contracts. Some of the analyses were conducted for specific life-cycle stage(s), while others were conducted for the whole lifecycle, depending on the focus of the parameter. The key findings are summarized by category.

For the goal and scope parameters, it was found that:

- A cut-off criteria using economic value was appropriate and a cut-off value below the 95%/0.5% would cause significant loss (up to 12% when using a 70% cut-off) of environmental impacts for the M&C stage but less so for the overall lifecycle;
- Exclusion of infrastructure was shown to result in a significant loss of impacts in the use-phase (up to 61%) and EOL stage (up to 48%) and likely also for the entire lifecycle;
- EOL allocation using a substitution method has a significant impact (up to 76%) on the M&C, M&R, and EOL stages using a landfill rate of 5% but less likely on the entire lifecycle;
- Asphalt allocation using various methods has a negligible impact on the overall lifecycle (less than 2%) and a notable impact (up to 6%) on the M&C and M&R stages; and
- Traffic using a non-linear growth rate has a significant (up to 20%) effect on the overall lifecycle impacts.

For inventory analysis, it was found that the use of:

- Progressive materials LCIA databases has a notable impact (up to 6%) on the M&C stage but less likely on the entire lifecycle;
- Progressive equipment LCIA databases has a small impact (up to 3.4%) on the M&C stage and thus a negligible effect on the entire lifecycle;
- Progressive technology LCIA databases incorporating a constant 4% annual emissions reduction in all processes can have a significant impact (up to 50%) on the entire lifecycle; and
- Two-way hauling distances can have a notable impact (up to 5%) on the M&C stage but less likely on the overall lifecycle impacts.

Finally, for impact assessment, it was found that:

- Primary energy as material contributes a notable impact (up to 35%) on the total lifecycle impacts and the gravity of this impact depends on the pavement types considered.

Overall, it was found that many of the parameters examined may have notable impacts on their affect stages (i.e., M&C, M&R, and EOL), but when the entire lifecycle is considered (i.e., the use-phase), the effects often diminish. Thus, the sensitivity of the results will depend largely also on the system boundaries of the individual LCA study.

CHAPTER 6

ASSESSING AND IMPROVING REGIONAL AND TEMPORAL UNCERTAINTY IN PAVEMENT LIFE-CYCLE INVENTORY DATA[16]

6.1 Motivation

In Chapter five, sensitivity analyses were used to evaluate important choices made in a pavement LCA; those analyses were able to address aspects of uncertainty to a degree, but not in the rigorous statistical manner provide by the uncertainty analyses presented in this chapter. In general, uncertainty in LCA may be introduced through imprecision, variability or unknowns related to models, inputs or data (ISO, 2006b), where the latter is the focus of this chapter. LCA practitioners often use a combination of primary and secondary data sources, the latter of which may not accurately represent the actual system processes due to discrepancies in technology, sample size, time period, etc. In order to acknowledge and incorporate potential inaccuracies from using secondary data sources, data uncertainty should be quantified and implemented in an LCA study to better understand the reliability of the overall LCA results. As noted in ISO 14044, consideration of uncertainty is especially important for comparative LCA studies that are disclosed to the public (2006b). Thus, understanding the full range of probable environmental impacts for a pavement project rather than a single deterministic value will provide decision makers with confidence when comparing LCA results.

In this work, a simplified comparative LCA is performed for the construction of two alternative designs of a new airport runway. The overall environmental impacts are given as distributions based on probabilistic distributions introduced through data uncertainty. The outcome of this work is relevant to both LCA practitioners and consumers. Two methods are proposed for incorporating uncertainty into the LCI data that can be used by practitioners, including first, simplistic probability distributions and second, an improved Bayesian updating technique. The differences in implementation and final LCA results are highlighted, along with the original results when using a deterministic LCA approach. Both practitioners

[16] Part of the work in this chapter has been published as "Development of a life-cycle assessment tool to quantify the environmental impacts of airport pavement construction" in *Transportation Research Record: Journal of the Transportation Research Board* (in press). The authors of this work include Rebekah Yang and Imad Al-Qadi. All figures, tables or data were created by the author of this dissertation.

and consumers should be aware of the effect that data uncertainty may have on the reliability of pavement LCA results, and examples of uncertainty's influence are demonstrated in this chapter.

6.2 Background

Uncertainty is an inherent part of the LCA methodology, which attempts to quantify as accurately as possible complex inputs and outputs of real-life product systems. However, additional information and techniques required to model and propagate uncertainties is often a stumbling block for LCA practitioners to incorporate uncertainty into their analyses. Ross et al. (2002) surveyed 30 LCA studies, of which less than 50% made references to problems associated with uncertainty and less than a third of that subset explicitly mentioned uncertainty. This omission of addressing uncertainty and problems associated with uncertainty are also very relevant to pavement LCA studies. Inyim et al. (2016) surveyed 32 pavement LCA studies and only two explicitly analyzed uncertainty related to environmental impacts (though others analyzed uncertainty concerning future pavement conditions and traffic behavior in the use-phase indirectly through sensitivity analyses).

Nonetheless, ISO 14044 guidelines do frequently suggest, and at times require, the use of uncertainty analysis, which is defined as a "systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability" (2006b). Huijbregts (1998) expanded on the different types of uncertainty and identified them as (1) parameter uncertainty, (2) model uncertainty, (3) uncertainty from choices, (4) spatial variability, (5) temporal variability, and (6) variability between objects and sources. Huijbregts then also recommended appropriate uncertainty analysis methods for each type of uncertainty, where probabilistic simulations were to be used for (1) and (6), scenario analyses for (3), and more complex modeling for (4) and (5). Later studies (Coulon et al., 1997; Bjorklund, 2002) have also surveyed how uncertainty is accounted for in LCA literature, finding that uncertainty analysis methods typically include expert judgement, correlation or regression analysis, analytical methods, fuzzy logic computations, Bayesian statistics, and stochastic modeling (e.g., Monte Carlo and Latin Hypercube). While treatments of each type of uncertainty may overlap, the specific type of uncertainty addressed in the remainder of this chapter is that which is related to LCI and specifically secondary data sources.

LCI data uncertainty can be incorporated using a qualitative or quantitative method. Regarding the former, Weidema and Wesnæs (1996) proposed a series of data quality indicators (DQI) that have been used and adopted in numerous subsequent studies and is currently implemented in the Ecoinvent LCI database (Weidema et al., 2013). In the original 1996 paper, the authors presented a data quality pedigree matrix (DQPM) with DQI including reliability, completeness, temporal correlation, geographical

correlation, and further technological correlation. A basic uncertainty is first estimated, and then a qualitative scoring of the data against the DQPM is performed, after which the scores are used to transform the basic uncertainty to a modified uncertainty using coefficients of variation. In addition to this qualitative method of addressing uncertainty, quantitative methods have also been implemented, such as that using Monte Carlo method. For example, a study by Lo et al. (2005) that will be referenced later in this chapter, used a combination of Monte Carlo and Bayesian statistics to estimate the uncertainty of GHGs related to landfilling and incinerating waste. The authors first considered generic, global inventory data and then used Bayesian updating methods to improve the data uncertainty in the LCA by 40-46% with region-specific inventory data collected in Taiwan.

While uncertainty analysis has not been widely applied in pavement LCA, recent studies have begun to explicitly address the effects of data uncertainty. In fact, FHWA's pavement framework document recommends that both sensitivity and uncertainty analyses be performed in the LCA interpretation phase (Harvey et al., 2016). An early mention of uncertainty in pavement LCA exists in a 1998 paper by Horvath and Hendrickson. The authors do not analyze uncertainty, but explicitly address and emphasize that the data uncertainty is likely to have a significant effect on the overall results. Since then, a handful of studies in the 2010s have incorporated uncertainty analyses into their assessments. Lin (2012) described an LCA software, Roadprint, that addresses parameter uncertainty in a select number of items including transportation distance, construction productivity, paving productivity, and material production. Aside from the last item whose uncertainty was based on a set of literature values, the other items were assessed probabilistically using default standard deviations of 0.05 times the mean. The results were reported as a 90% confidence interval from a set of Monte Carlo simulations, and the author reported only a slight variation in results due to the default standard deviation used.

Later works starting in 2013 also addressed uncertainty using a combination of qualitative and quantitative approaches. Noshadravan et al. (2013) considered various types of uncertainties, including data measurement uncertainty that was addressed with default lognormal distributions, parameter uncertainty that was addressed with a DQPM, and finally use-phase models that had built-in probabilistic characteristics. Equivalent asphalt and Portland cement concrete designs were compared in a complete LCA using Monte Carlo simulations to propagate the uncertainties. A comparative indicator variable (based on Huijbregts et al., 2003) was calculated as the ratio of GHGs between the two designs at each iteration of the simulations in order to determine which design had lower impacts. Xu et al. (2014) expanded on this work and added scenario-based analysis for uncertainty factors that mainly focused on use-phase parameters.

In 2016, Gregory et al. formulated a framework for applying uncertainty analysis in LCA that included a three step escalation process of first performing a probabilistic analysis to characterize

uncertainty, then determining influential parameters if the probabilistic analysis was not conclusive, and finally refining estimates of the influential parameters if they were determined to be relevant in the previous step. Finally, Yu et al. (2016) calculated uncertainty related to the energy intensive of producing pavement materials. The authors used a DQPM to provide initial scores for a set of data values that were then transformed to a beta distribution. The data values were each weighted using various methods and then run with a Monte Carlo simulation to obtain the final energy values.

While progress has been made on incorporating uncertainty considerations into pavement LCA, the studies existing thus far generally assign uncertainties based on a simplistic DQPM or default distributions that do not incorporate known DQI relationships. Thus, this chapter discusses methods to build and improve upon the use of a DQPM by utilized biased information about the original data source and the desired data source through Bayesian updating.

6.3 Objective

The main objective of this work is to perform a comparative LCA for airport runway construction, taking into account the uncertainty of secondary data sources using two methods. The first method will utilize an existing qualitative DQPM to assign probabilistic distributions to the data, while the second method will build upon the first by using Bayesian updating techniques to improve the distributions through regional and temporal corrections. In addition, an LCA tool will be developed to evaluate a case study of two alternative pavement designs; one based on the actual design of a 2015 runway using various sustainable materials and the other without the use of sustainable practices.

6.4 Goal and Scope

The LCA in this work was performed in accordance with LCA guidelines by the ISO 14040 series (2006a). The intended audience for this study is airport operators, designers, and contractors who are interested in evaluating the environmental sustainability of their airport pavements using LCA as well as general pavement LCA practitioners and consumers who are interested in the effect of data uncertainty on overall LCA results. This study is a standalone comparative LCA study that will calculate the environmental burdens directly associated with the construction of airport pavement. A partial life-cycle approach is used in this study that considers only the material production and initial construction stages of the product system, as a major focus of this project is to incorporate data uncertainty from the unit processes relevant to these two initial stages.

The case study chosen for this work includes the newly constructed 10R-28L runway at Chicago O'Hare International Airport. The 10R-28L runway, which opened in October 2015, is part of a $6.6 billion

series of infrastructure projects referred to as the O'Hare Modernization Program, which began in 2001. The runway is 13,000 feet long and 150 feet wide with 35-foot wide shoulders. The original contract also includes 35-foot wide connecting taxiways as well as associated lighting and signage, but the case study focuses specifically on the runway.

The mainline and shoulder pavement designs are shown in Figure 6.1. In the mainline design, the PCC contains appropriately 23% fly ash. The subsequent bituminous concrete base was made using WMA foaming technique and contains approximately 20% RAP and 2.5% RAS. The asphalt treated permeable base (ATPB) is HMA with approximately 5% RAP and 2% RAS. Lime kiln dust was used to stabilize the subgrade. In the shoulder design, WMA was used for both the bituminous concrete surface and base layers, the former of which had approximately 16% RAP and 2.5% RAS. The aggregate subgrade consisted of crushed concrete from previous PCC runways at O'Hare.

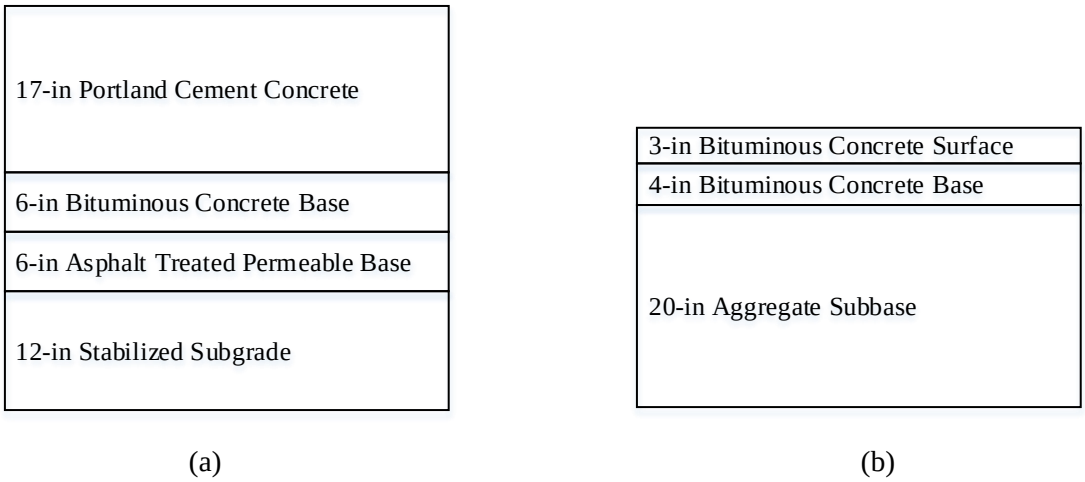


Figure 6.1: (a) Mainline and (b) shoulder pavement designs for 10R-28L.

The functional unit used in this analysis is one square yard. Typically, the environmental impacts are normalized over the spatial and temporal dimensions of the project, but in this case, only the initial construction is considered, so the temporal dimension is one year. The product system includes the mainline, shoulders and all pavement layers, excluding lighting, signage, drainage, landscaping, and other supporting elements. The system boundaries of the study, shown in Figure 6.2, exclude the use, maintenance, and EOL stages. In addition, any delays due to initial construction are also removed from the scope and assumed to be negligible for the new runway construction that is analyzed in the case study.

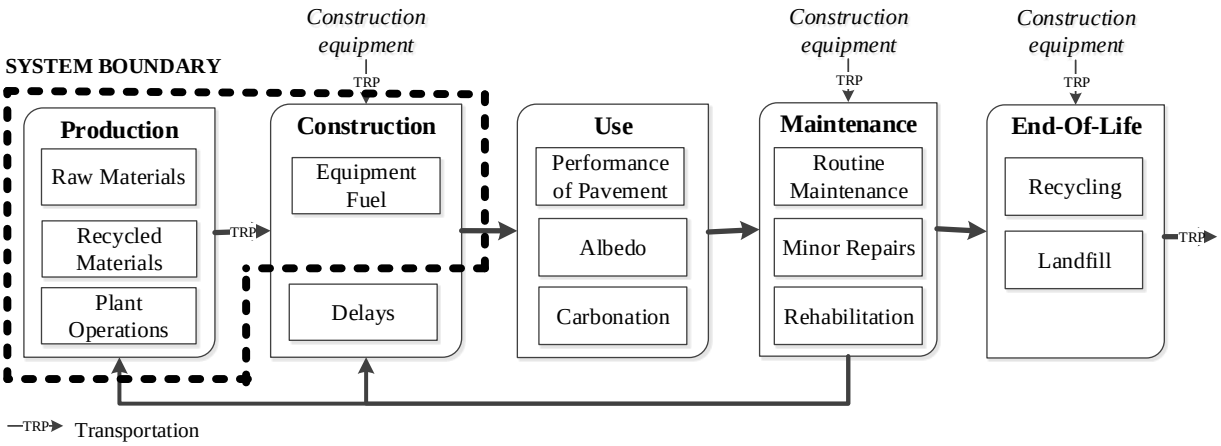


Figure 6.2: System boundaries of the LCA study.

6.5 Inventory Analysis

In this study, both primary data and secondary data were utilized. Primary data regarding the project details were collected from contract documents and drawings from the 10R-28L runway project to obtain dimensions, mix designs, and other project details. Data were also collected concerning fuel usage for the contract. The fuel usage was collected on a daily basis, but it was not clear which equipment were used for which activities covered by the contract. Thus, due to the significance of the runway work, it was assumed that all fuel used during the days in which major construction work on the runway was scheduled to occur (May 21, 2014 to January 21, 2015) is attributed to the 10R-28L runway. It is noted that this likely overestimates the amount of fuel allocated to the runway construction included in the system boundaries, as other activities such as lighting and signage installation were also taking place at the same time.

Secondary data were used for all of the environmental inventory information. The initial set of LCI data was obtained from literature sources and reports as well as a commercial database, US-EI 2.2, which provides a comprehensive set of upstream processes. A summary of the major unit processes and data sources used are given in Table 6.1.

Table 6.1: Summary of Secondary Data Sources

Unit Process	Unit	Data Sources
Prime coat	short ton	Yang (2014)
Tack coat	short ton	Yang (2014)
Asphalt binder	short ton	Yang (2014)
Portland cement	short ton	Marceau et al. (2006)
Natural aggregate	short ton	Marceau et al. (2007)
Manufactured aggregate	short ton	Marceau et al. (2007)
Steel	short ton	US-EI 2.2
Lime	short ton	US-EI 2.2
Fly Ash	short ton	Chen et al. (2010)
RCA from PCC runways	short ton	NTD LLC (2009)
RAP	short ton	assume same as RCA
RAS	short ton	assume same as RCA
Lime kiln dust	short ton	assume negligible
Water reducing admixture	ounce	Intron (2006a)
Water retarding and reducing admixture	ounce	Intron (2006b)
High range admixture	ounce	Intron (2005)
Air entraining admixture	ounce	Intron (2006c)
Ready mix concrete plant	yd^3	Marceau et al. (2007)
HMA plant	short ton	Young (2007)
WMA plant (foaming)	short ton	Young (2007)
Trucking	short ton-mile	US-EI 2.2
Various equipment (diesel)	gallon	US-EI 2.2, MOVES 2014b
Various equipment (2-stroke gasoline)	gallon	US-EI 2.2, MOVES 2014b
Various equipment (4-stroke gasoline)	gallon	US-EI 2.2, MOVES 2014b

The unit processes compiled in Table 6.1 were modeled to represent as closely as possible the case study of a 2015 runway construction in Illinois. The processes related to asphalt materials (i.e. prime and tack coat, asphalt binder) were developed based on a model representing petroleum production in the U.S. Midwest (Yang, 2014). The Portland cement, natural and manufactured aggregate production, and ready mix concrete plant processes were modeled based on inventory collected by the Portland Concrete Association meant to represent the U.S. industry (Marceau et al., 2007). Various default processes from the US-EI 2.2 database were used when insufficient secondary data was found, such as processes related to steel production, trucking, and lime production. The production of admixtures were taken from a set of environmental product declaration from the European Federation of Concrete Admixture Association (Intron 2005, 2006a, 2006b, 2006c). The data used to model HMA and WMA plant operations were taken from information by the U.S. National Asphalt Pavement Association (Young, 2007). Finally, environmental impacts regarding offroad vehicle operations were modeled based on simulations done using EPA's MOVES2014b software (2014), where the simulation parameters reflected conditions found in Cook County, Illinois, the location of the case study.

Key assumptions have been made regarding cut-off rules for upstream and downstream processes. Upstream infrastructure impacts are not included (e.g., construction and maintenance of plant facilities,

manufacture and upkeep of equipment). In the construction stage, only impacts related to fuel production and combustion in different types of equipment are considered. Additional emissions such as dust particulates due to material handling and laying is out of the scope of this study. Any processes related to worker commuting and human labor are not considered. Finally, a cut-off allocation method was chosen for recycled materials such as RAP, RAS, and recycled concrete aggregate (RCA). Thus, only the environmental burdens directly associated with processing recycled materials are attributed to the recycled material; all environmental benefits associated with recycling are given to the system using the recycled material. The methodologies, parameters, and data sources used to characterize the uncertainty of the secondary LCI data are described in subsequent subsections.

6.6 Impact Assessment

This LCA study considers the environmental metrics of TPE consumption and GHGs. TPE or cumulative energy demand includes primary energy used as fuel in addition to that used as material (e.g., plastics and asphalt binder which are petroleum products that contain embodied energy). The impact assessment methodology used to calculate GHGs is EPA's TRACI v 2.1.

6.7 LCA Tool

A tool was developed in Microsoft Excel using VBA in order to facilitate the implementation of LCA and uncertainty analyses for the case study as well as future analyses. The tool is implemented through a series of graphical user interfaces following the high-level framework of the tool depicted in Figure 6.3. The user begins a project that can include a variety of construction activities. These activities can be major tasks occurring during initial construction as well as future maintenance and rehabilitation as needed. For each activity, the user then specifies details regarding the activity such as the cost and year performed as well as the materials, equipment, and plant operations required. For the latter three components, the user selects unit processes from the LCI database (e.g., asphalt binder) and indicates the quantity of the material or fuel usage of the equipment needed as well as the hauling or mobilization distance. The results of the project are calculated in a bottom-up method by aggregating the environmental impacts from each unit process selected for each activity.

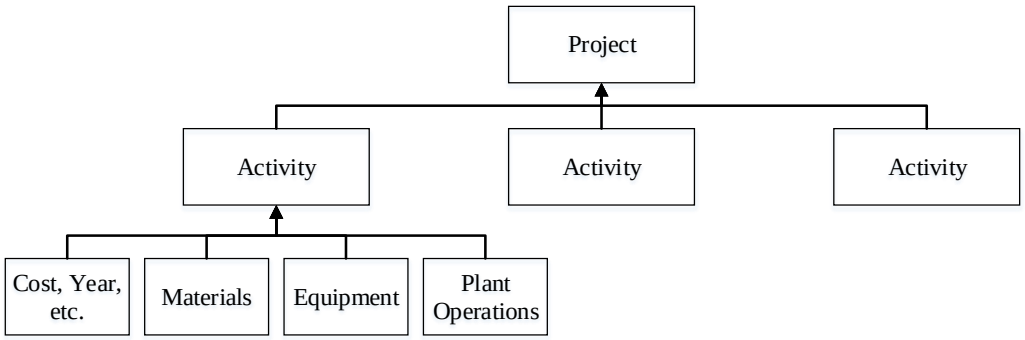


Figure 6.3: Framework of the partial LCA tool.

6.8 Data Uncertainty Using a Pedigree Matrix

Two methods are considered in this study to assess the uncertainty associated with the secondary LCI data listed in Table 6.1. The first method involves the use of the DQPM adopted by the commercial Ecoinvent LCI databases (Weidema et al., 2013). In this method, the quality of the inventory data is assessed using six factors (U1 to U6): completeness, reliability, geographical correlation, temporal correlation, further technological correlation, and sample size. For each factor, a score of 1 to 5 is qualitatively given to the inventory data, with each score corresponding to a quantitative squared geometric standard deviation (sGSD). For example, with regards to the temporal correlation factor (U3), a score of 2 is given if the data were obtained less than 6 years difference from the reference year. This score of 2 for temporal correlation corresponds to a sGSD of 1.03 for this parameter, which is then the value assigned to U3. A sGSD of 1.00 is given to data that score 1 (the best) for any factor, which implies no uncertainty in the data.

After assigning values to all factors U1 to U6, the aggregated sGSD (σ_g^2) is calculated for each inventory data as shown in Equation (6.1), so that the lognormal distribution of its environmental impacts can be quantified.

$$\sigma_g^2 = e^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2}} \quad (6.1)$$

One major difference in the way that Ecoinvent uses the DQPM is that the database assigns these values at the individual emissions level while this study assigns the data quality directly to the characterized impacts at the unit process level. A reproduction of the DQPM used by Ecoinvent is given in Appendix A.

After the sGSD's for all unit processes have been assigned, a series of Monte Carlo simulations are used to propagate the lognormal distributions of the unit processes in the LCA calculations. The sGSD is assigned directly to the environmental impacts (i.e., TPE and GHG) and 1000 simulations are run to

ultimately produce a set of total LCA results that can be characterized using parameters from a typical normal distribution.

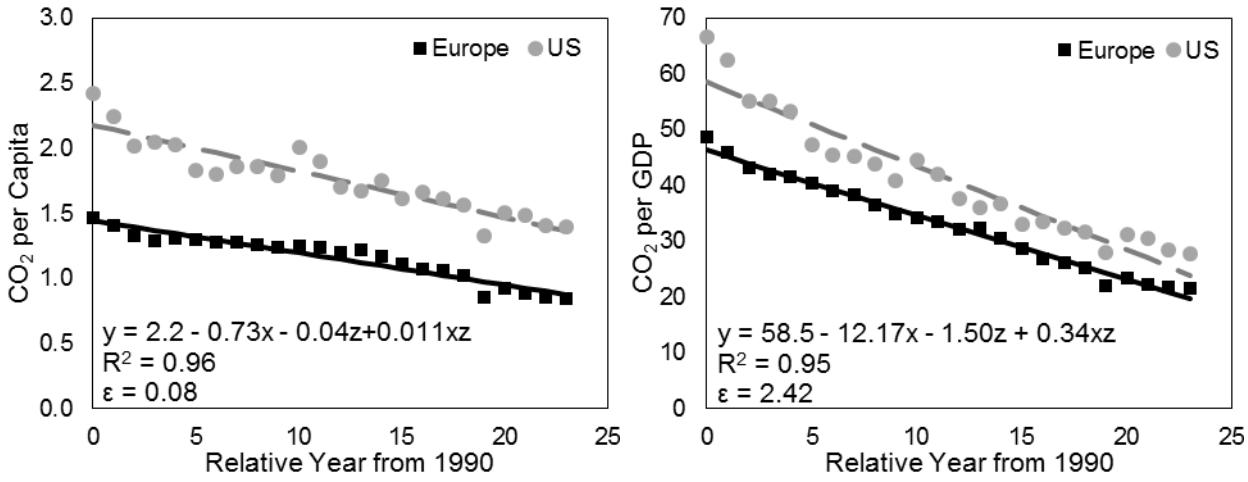
6.9 Improved Data Uncertainty Using Bayesian Updating

Regarding temporal and regional aspects, the DQPM method assigns the same unbiased probabilistic distribution to data that was collected five years before the desired time period as well as to data collected five years after the desired time period. Similarly, the DQPM method may assign the same unbiased probabilistic distribution to data collected in a developing country versus a developed country if they are not in the same geographical location as the desired regional context. However, in both of these examples, existing trends and data can be used to apply more biased distributions to the data that better characterize the uncertainty of the data. For example, data collected five years before the desired time period would be expected to have greater environmental impacts than data collected five years after the desired time period due to improvements in process efficiency or stricter environmental regulations over time. Similarly, data collected from a developed country that has more rigid policies on environmental emissions may be expected to have lower environmental impacts than data collected from a developing country that may not have enforceable environmental regulations.

The second method of assessing uncertainty thus builds upon and improves the first method, updating the lognormal distributions of the previous unit processes. A Bayesian inference method is used with observations based on estimated temporal and regional trends. Lo et al. 2005 uses a similar Bayesian Monte Carlo (BMC) approach to update uncertainty distributions for inventory data related to waste incinerators using international emission factors updated with measured data values from national and regional incinerators. In this study, however, measured data were not available, so regression trends were used to produce observations in order to update the data based on regional as well as temporal considerations.

In order to update the original lognormal distributions from the first method, new data were generated synthetically from open source data. The secondary LCI data utilized in this study range in years from the late 1999s to 2010s, though the case study itself was constructed in 2015. In addition, some of the data originated in Europe, potentially misrepresenting the processes they are intended to model in the US case study context. Thus, there is a need for the new data in the Bayesian updating process to improve the original data with respect to region and time. As it was not possible to obtain a set of measured data points for each unit process in Table 6.1, regression models were developed to estimate the new data. The data used for the models were taken from the World Resource Institute's Climate Analysis Indicators Tool (CAIT) of historical CO_2 emission data by country (2017). The emissions are grouped by various categories

based on source and sector usage, including the "Manufacturing/Construction" category used in the regression models. Data from 1990 to 2013 were used for the US as well as for the European Union prior to 2004[17] (EU15). Using socio-economic values reported by CAIT, the total annual CO_2 emission values were normalized by population (per capita) and by economic growth (per gross domestic product [GDP]). The resulting linear regressions are shown in Figure 6.4, where y is the normalized CO_2, x is a binary regional variable representing 1 if Europe and 0 if US, and z is an integer time variable calculated as the relative year from 1990.



(a) (b)

Figure 6.4: Regression of CAIT data for CO_2 (a) per capita and (b) per GDP.

In general, the emission factors decrease over time and Europe tends to have lower normalized emissions than the US. The decreases in CO_2 values for the per capita and per GDP models are projected to be approximately 23% and 40%, respectively, over a ten year period from 2005 to 2015. This corresponds to a 2.6% and 5.0%, respectively, annual decrease in impacts per year. As a comparison, the EPA found that CO_2 emissions from light-duty automobiles in the US decreased by 22% from 2004 to 2015 (EPA, 2016), implying that the steep slope in the GDP model may be influence by external factors. In general, GHGs per capita and per GDP have been found to be notably different (Grant et al., 2013). Emissions per capita take into account population growth in the country, but normalization by population may not be consistent with the overall industrial, transportation or other activities performed in the country. On the other hand, emissions per GDP may better represent the activities performed in the country, but they too can also be misinformed due to fluctuations with national or global economic value. Thus, in this study,

[17]The countries included in the EU in 2015 included Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and United Kingdom.

both regressions will be used and the results compared. It should be noted that the observed data sample in this study was generated artificially based on recognized trends. If data are available, the observed data should be sampled from the physical representations of the unit processes (e.g., material production facilities).

Using Bayesian updating, a prior distribution can be updated to a posterior distribution using newly observed data. In BMC, the posterior distribution can be calculated using Equation (6.2), where O is the newly observed data, C_i is the model output of the ith Monte Carlo simulation out of N total simulations, p_i' is the posterior probability, L is the likelihood, and p_i is the prior probability (Brand & Small, 1995; Lo et al., 2005).

$$p_i'(C_i|O) = \frac{L(O|C_i)p_i(C_i)}{\sum_i^N L(O|C_i)p_i(C_i)} \quad (6.2)$$

In this study, the prior distribution p_i is taken to be the lognormal distribution determined using the DQPM in the first method. The observed data are estimated using the regression models found in Figure 6.4. The emission values for the original year (i.e., between 1999 – 2012) and region (i.e., US or Europe) of the unit process is compared to the emission values for the case study year (i.e., 2015) and region (i.e., US), and the corresponding factor of difference from the regression model is proportionally applied to the original unit process impacts to obtain the newly observed data. The standard error from the regression is applied to the observed data following a normal distribution. By assuming that the observed data follows a normal distribution, Equation (6.3) can be used to analytically calculate the likelihood function (Brand & Small, 1995).

$$L(C_i|O) = \frac{1}{\sqrt{2\pi\sigma_\epsilon}}\exp\left(-\frac{1}{2}\left[\frac{O - C_i}{\sigma_\epsilon}\right]^2\right) \quad (6.3)$$

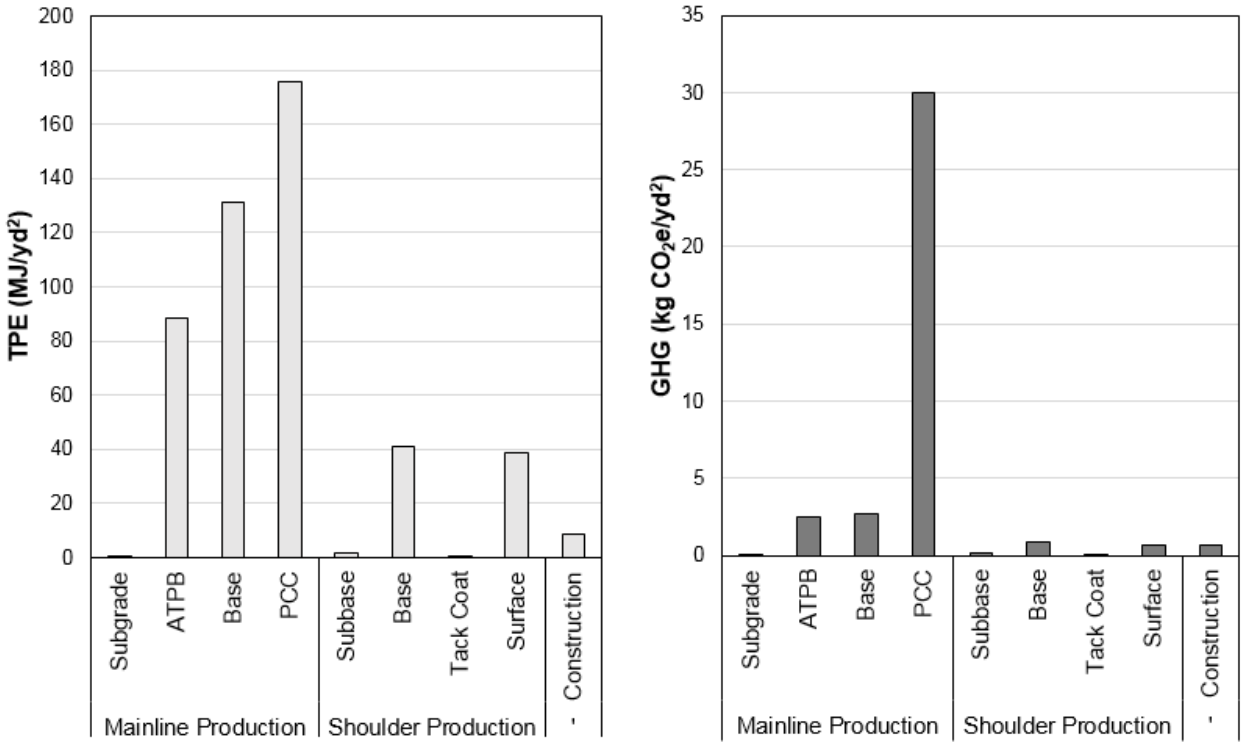
The posterior distribution is determined by sampling using 1000 Monte Carlo simulations to generate a set of probabilities. Assuming that the posterior distribution is also normally distributed, the mean and standard deviation of the posterior distribution is calculated using the sampled probability density function.

6.10 Deterministic and Probabilistic Results

The results of the comparative LCA are first discussed in detail for the original runway design using the deterministic results. Then, results for both alternative designs are given from the simplistic DQPM probabilistic method followed by results using BMC.

6.10.1 Deterministic results

The partial life-cycle analysis found that the overall environmental impacts of runway construction were 485 MJ/yd^2 for TPE and 37.5 kg CO_2e/yd^2 for GHG. The environmental impacts are broken down by material production (including transportation to site) of various structural components as well as construction in Figure 6.5.



(a) (b)

Figure 6.5: (a) TPE and (b) GHG impacts from the production of various structural components as well as the overall construction of the runway.

The components in Figure 6.5 are ordered from bottom to top structurally for the mainline and shoulder, which is also how the environmental impacts generally increase. This is due to the fact that the binder amounts (i.e., asphalt binder in ATPB and WMA base and Portland cement in PCC) increase in the upper layers of the pavement, and the production of these binders has a high environmental impact (i.e. asphalt binder requires a large amount of energy to extract and refine from crude oil). The TPE reported includes the feedstock energy, which is up to seven times the process energy to produce the binder (Yang, 2014), and thus increases the TPE contribution for the base layers. On the other hand, Portland cement requires a great deal of energy to produce in a kiln, but it also emits large amounts of carbon dioxide through the calcination process. Thus, the combined HMA products (i.e., ATPB, WMA base, and WMA surface)

tend to have higher relative TPE contribution while the PCC has a higher relative GHG contribution. The lime-stabilized subgrade and RCA subbase have small contributions, as the materials used in these processes are by-products (i.e., lime kiln dust) or recycled materials (i.e., RCA). Finally, the production and combustion of fuel used during the construction of the runway itself comprise less than 2% of the total TPE and GHG.

A more detailed breakdown of the individual unit processes that make up the project analysis are shown in Figure 6.6. The major processes contributing to TPE consumption and GHG emissions are the production of Portland cement, asphalt binder, and aggregate as well as asphalt and PCC plant operations. Again, the percentage contributions of Portland cement and asphalt binder are not the same for TPE and GHGs due to the reasons mentioned. The TPE and GHGs from plant operations differ because asphalt plants in Illinois largely utilize natural gas, which emits less GHGs than other fossil fuels when consumed. The "other" category depicted in Figure 6.6 includes the production of admixtures, tack coat, and lime kiln dust (transportation only).

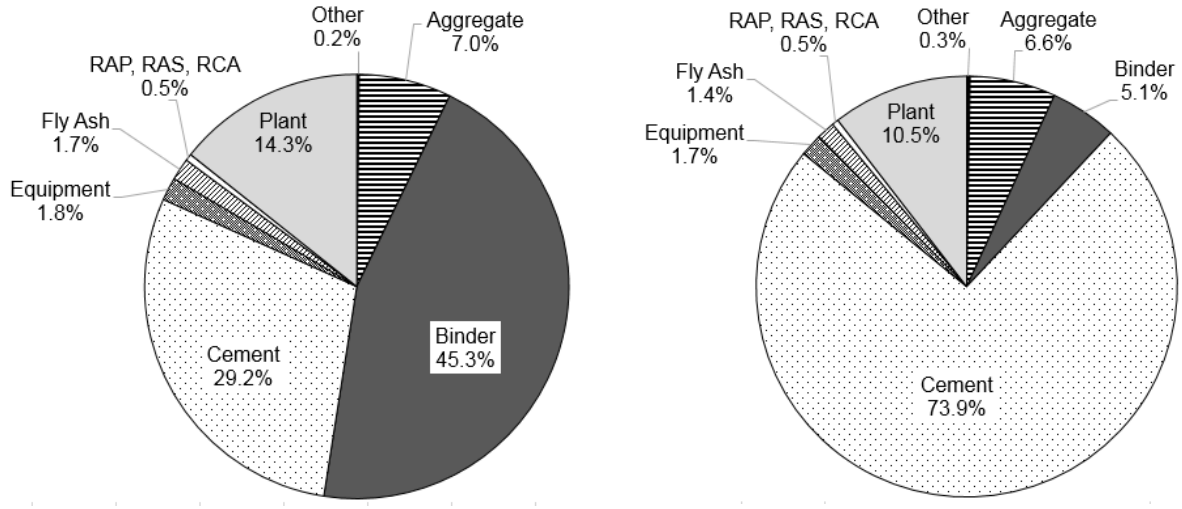
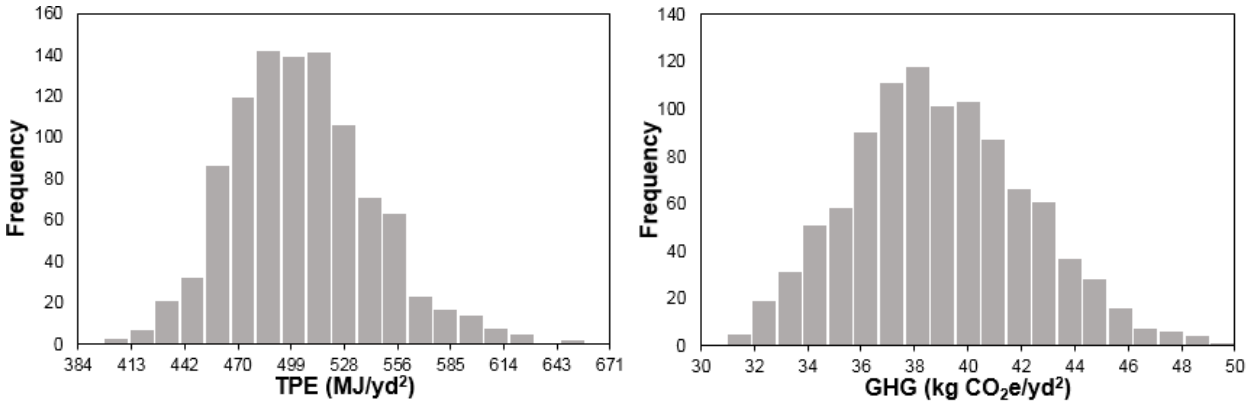


Figure 6.6: Contribution of various material production processes and equipment usage to the total (a) TPE and (b) GHGs resulting from runway construction.

6.10.2 Basic probabilistic results

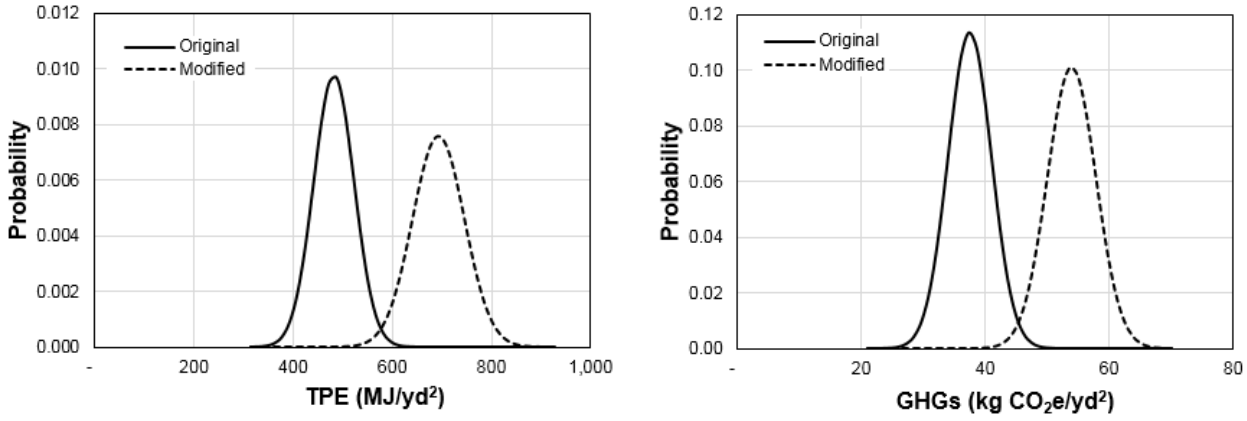
The DQPM probabilistic results discussed in this subsection include those from the original runway design as well as the alternative runway design. The impacts for the original runway design are given in Figure 6.7 based on 1000 Monte Carlo simulations. The set of results are normally distributed with a mean of 482 MJ/yd^2 (standard deviation [SD] 41 MJ/yd^2) for TPE and 37.5 kg CO_2e/yd^2 (SD 3.5 kg CO_2e/yd^2) for GHGs. These mean values are similar to the total impacts found in the deterministic results.



(a) (b)

Figure 6.7: DQPM simulation results for (a) TPE and (b) GHG for the original project.

The original 10R-28L runway construction project analyzed includes various sustainable strategies such as the use of recycled material and warm-mix technology. A modified alternative design was also analyzed that did not included these sustainable strategies. RCA was replaced with manufactured aggregates and the aggregate portions of RAS and RAP were replaced with manufactured aggregates, while the recycled asphalt binder content were substituted with virgin binder. The WMA plant operations used to model the WMA base and surface mixes used in the pavement were replaced with HMA plant operations. Finally, the fly ash used in the PCC slabs was replaced with virgin Portland cement. One-to-one substitutions were used and it was assumed that the modified mixes had the same functionality of the original mixes. Figure 6.8 shows the distribution of 1000 Monte Carlo simulations for the impacts of the original and modified mixes.



(a) (b)

Figure 6.8: DQPM results for (a) TPE and (b) GHG for the original and modified projects.

The modified design has a mean of 693 MJ/yd_2 (SD 52 MJ/yd_2) for TPE and 53.9 kg CO_2e/yd^2 (SD 3.9 kg CO_2e/yd^2) for GHG. The results for both environmental impacts of the modified design are statistically different than those of the original design at an alpha value of 0.05. In this study, the two cases examined were extremes and thus more straightforward comparisons, where one incorporated sustainable strategies while the other replaced major sustainable strategies with those that were expected to result in more environmental impacts. Thus, there are limitations in the simplicity of the one-to-one material substitutions used in addition to limited scope of including only initial construction in this analysis.

6.10.3 Bayesian updating results

In the improved BMC method, the lognormal distributions from the DQPM method were taken to be the prior distributions while the observed data were obtained from two regression models. Examples of the prior and posterior distributions are included in Figure 6.9 for RCA processing and air entraining (AE) admixture production using the per capita and per GDP regression models.

The original data for RCA process were obtained in 2005 in the US, while that for AE admixture were obtained from 2000 European data. Compared to the prior mean value for RCA (1.5), the mean updated value is significantly lower (0.88) for the GDP model due to the GDP model's steep time correction and slightly lower (1.18) for the per capita model. Compared to the prior mean value for AE admixture (0.0030), the mean updated value based on the GDP model is notably lower (0.0019) due again to the time correction while the mean update value for the per capita model is actually higher (0.0032) because the regional correction from Europe to US data overcomes the time correction in the per capita model. Thus, using different regression models and observed values will affect the overall LCA results. A summary of the prior, observed, and posterior mean values and SD for all unit processes are given in Table 6.2.

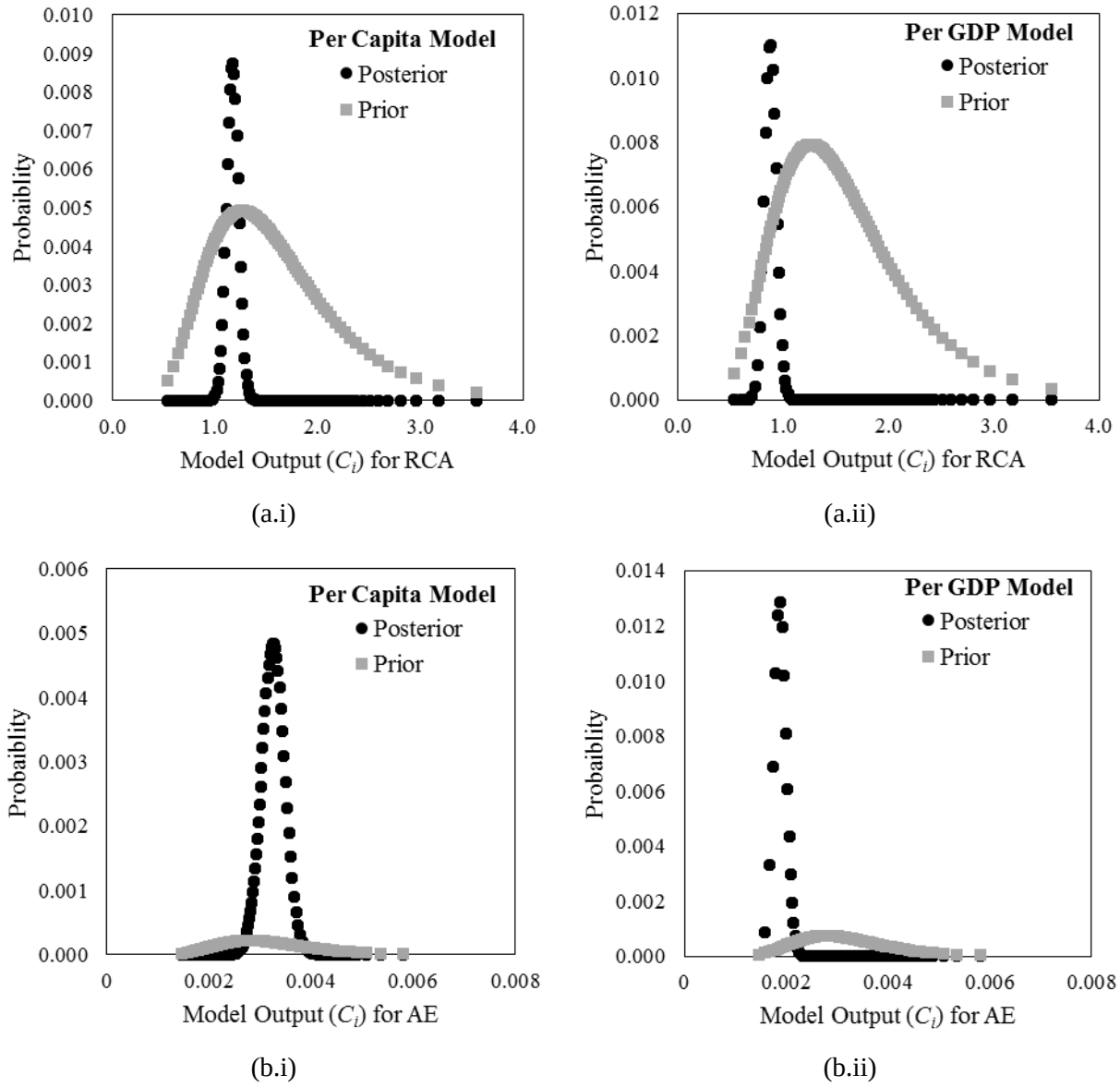


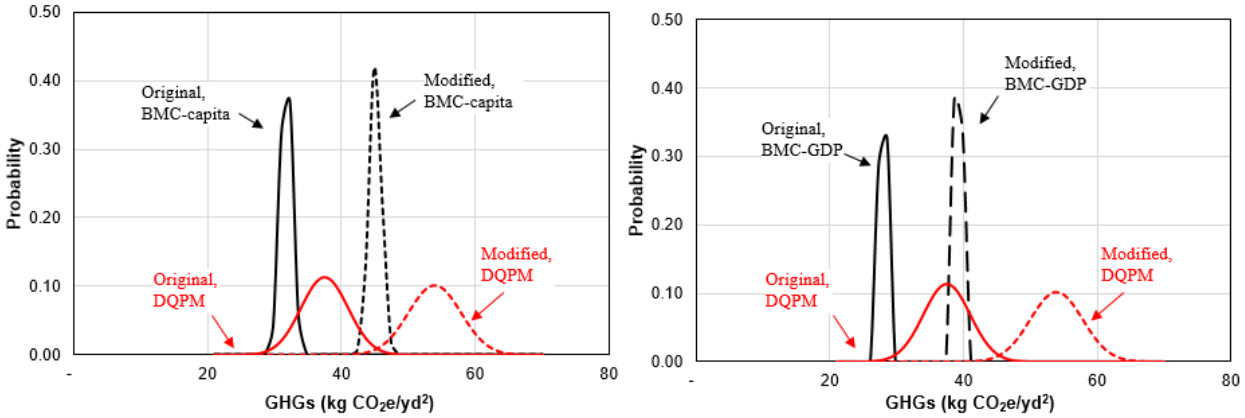
Figure 6.9: Prior and posterior distributions for (a) RCA and (b) AE admixture production using the (i) per capita and (ii) per GDP regression models.

Table 6.2: Summary of Probabilistic Characteristics of the Secondary Data Sources for GHGs (kg CO_2e/unit)

Unit Process	Unit	Prior Mean	Prior sGSD	Observed Mean	Observed SD	Posterior Mean	Posterior SD
AE admixture	ounce	3.05E-03	1.34E+00	3.29E-03	2.29E-04	3.22E-03	2.24E-04
Asphalt binder	short ton	3.66E+02	1.23E+00	3.38E+02	2.01E+01	3.39E+02	1.90E+01
Portland cement	short ton	1.16E+03	1.13E+00	9.30E+02	4.81E+01	9.77E+02	3.98E+01
Fly ash	short ton	6.67E+01	1.29E+00	8.84E+01	7.56E+00	8.24E+01	6.89E+00
Lime	short ton	7.05E+02	1.31E+00	5.42E+02	2.68E+01	5.45E+02	2.64E+01
Lime kiln dust	short ton	--	--	--	--	--	--
Manufactured aggregate	short ton	4.56E+00	1.58E+00	3.17E+00	1.42E-01	3.16E+00	1.42E-01
Natural aggregate	short ton	3.15E+00	1.58E+00	2.19E+00	9.82E-02	2.18E+00	9.85E-02
Prime coat	short ton	3.23E+02	1.27E+00	4.39E+02	3.85E+01	4.03E+02	3.53E+01
RAP	short ton	1.49E+00	2.19E+00	1.17E+00	5.93E-02	1.16E+00	6.10E-02
RAS	short ton	1.49E+00	2.19E+00	1.17E+00	5.93E-02	1.16E+00	5.73E-02
RCA from PCC runways	short ton	1.49E+00	1.50E+00	1.17E+00	5.93E-02	1.18E+00	6.00E-02
Steel	short ton	1.39E+03	1.25E+00	1.17E+03	6.31E+01	1.18E+03	6.10E+01
Tack coat	short ton	3.23E+02	1.27E+00	4.39E+02	3.85E+01	4.01E+02	3.52E+01
Water reducing Admixture	ounce	6.79E-03	1.40E+00	7.48E-03	5.31E-04	7.35E-03	4.95E-04
Mineral filler	short ton	--	--	--	--	--	--
Ready mix concrete plant	yd^3	4.34E+00	1.13E+00	3.49E+00	1.80E-01	3.67E+00	1.56E-01
WMA plant (foaming)	short ton	1.73E+01	2.02E+00	1.42E+01	7.53E-01	1.41E+01	7.50E-01
HMA plant	short ton	1.91E+01	2.02E+00	1.57E+01	8.31E-01	1.55E+01	8.03E-01
Equipment (Diesel)	gallon	1.23E+01	1.05E+00	1.26E+01	8.38E-01	1.24E+01	4.02E-01
Truck	short ton-mile	1.15E-01	1.25E+00	9.62E-02	5.21E-03	9.74E-02	4.66E-03

The resulting posterior distributions defined in Table 6.2 were then used to run another set of 1000 Monte Carlo simulations in the LCA tool. Probabilistic results comparing the original and modified runway designs are given in Figure 6.10 for distributions based on both the per-GDP and per-capita models. The DQPM results are also included. For both the original and modified design results, the two BMC result sets overlap with the left tail of the DQPM results. In general, the impacts decrease with the improved BMC method because the original LCI data sources were largely from the 2000s. With the time correction applied in the BMC regression models, the improved impacts are now shifted to the left to represent an estimated reduction in environmental impacts over time. Between the two BMC results sets, the BMC-GDP results show both original and modified distributions shifted over to the left more so than the BMC-capita model. In fact, the modified BMC-GDP results actually fall on the peak of the original DQPM results. This implies a significant shift in results, and casts doubt on whether the GDP regression model appropriately generalizes the per unit process reduction in CO_2 emissions over time. However, the BMC-capita results also are shifted to the point where the modified BMC-capita results barely overlap the modified BQPM results. Thus, while

the comparative results still show the original design having lower environmental impacts than the modified design, the values of the results themselves were lowered significantly by incorporating updated information.



(a) (b)

Figure 6.10: Probabilistic results using the DQPM and BMC methods for the original and modified projects using the (a) BMC-capita and (b) BMC-GDP approaches.

Overall, the resulting BMC distributions are also narrower in Figure 6.8 and have a smaller deviation than the DQPM distributions. This reduction in uncertainty is expected due to the smaller standard deviations of the observed data that were applied in the BMC method. However, while the BMC method altered the probabilistic results significantly with both the BMC-GDP and BMC-capita models, the observed data generated by the regression models only considered time and regional aspects. Only two out of six of the data quality parameters (U1 to U6) were updated in the BMC method, and the remaining uncertainties from completeness, reliability, further technological correlation, and sample size were not addressed in the new observed data or carried over from the prior distribution. Thus, the uncertainty of the posterior distributions were likely underestimated, which led to the drastic reduction of uncertainty in the BMC results in Figure 6.8.

For all results, the original designs have a significantly lower GHG impact than the modified designs when evaluated at a confidence level of 95%. In addition, the uncertainties of the difference in the designs are reduced as the DQPM distributions overlap in the two designs, while the BMC results show no discernable overlap. A summary of the major statistical properties of the results for each of the three methods used in this study are given in Table 6.3. It should be noted that the functional unit is in yd^2 and the total area of the runway was approximately 950,000 yd^2. Thus, while the standard deviations are small per functional unit, they result in large variations on a project level.

Table 6.3: Summary of Results for the Original and Modified Designs for all Analysis Methods

Environmental Impact	Case	Method	Mean	Standard Deviation	95% Confidence Interval
TPE (MJ/yd^2)	Original	Deterministic	485.38	--	--
		DQPM	482.41	40.80	(484.94, 479.89)
	Modified	Deterministic	695.22	--	--
		DQPM	693.48	52.46	(696.73, 690.23)
GHG ($kg\ CO_2e/yd^2$)	Original	Deterministic	37.55	--	--
		DQPM	37.48	3.51	(37.70, 37.26)
		BMC-GDP	27.92	0.42	(27.95, 27.89)
		BMC-Capita	31.76	0.90	(31.82, 31.70)
	Modified	Deterministic	53.96	--	--
		DQPM	53.93	3.93	(54.17, 53.68)
		BMC-GDP	39.21	0.50	(31.82, 31.70)
		BMC-Capita	45.05	0.94	(45.11, 45.00)

6.11 Summary

The main goal of this chapter was to assess and improve data uncertainty from secondary LCI sources in pavement LCA. Two methods were used to incorporate uncertainty into an environmental analysis, including one using a qualitative data quality assessment and another using Bayesian updating. An LCA tool was developed to implement the uncertainty analysis in the evaluation of a new runway construction. Key findings are summarized below:

- A DQPM was used to qualitatively assign lognormal distributions to each unit process in the LCA in order to run Monte Carlo simulations for the analysis, which resulted in a distribution of impacts with a mean values similar to that of the deterministic results;
- Regression models were used to generate newly observed data for the BMC method by quantifying the relationship between normalized CO_2 emissions over time and between the US and Europe;
- CO_2 emissions regressed over time were steeper when calculated per GDP then per capita, resulting in an overall reduction in LCA results with the BMC-capita method and more so with the BMC-GDP method as compared to the DQPM and deterministic results;
- Applying the BMC method was used to significantly alter the environmental impacts based on temporal and regional adjustments as well as reduce overall uncertainty in the results; and
- Comparative LCA studies were performed with varying ways of considering (or not considering) data uncertainty, and while the overall conclusion of which alternative design had a greater environmental impact was the same, the distribution of results varied widely among the methods.

Overall, this work presented two ways of considering the uncertainty of secondary data sources within pavement LCA. The case study showed that incorporating uncertainty into a pavement LCA can lead to a better understanding and perspective concerning the range of expected results, which will allow decision

makers to compare alternative designs in a more informed way. While progress was made to assess and improve data uncertainty in LCA, future work in this area includes addressing data quality issues beyond those related to time and region as well as expanding the uncertainty analysis to consider model and input types of uncertainty.

CHAPTER 7

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Summary

Various issues regarding the application and interpretation of LCA results for pavement systems were investigated in this work. The framework and implementation of a full roadway/roadside pavement LCA software was gradually developed in the first half of the dissertation followed by a detailed treatment of various LCA project case studies and related sensitivity and uncertainty analyses in the second half of the dissertation. Regarding the first half, LCI inventory data for the production of pavement materials were collected for Northern Illinois in order to calculate environmental impacts of asphalt mixtures with recycled materials. Careful attention was given to compile and model unit processes that as best as possible reflected regional aspects. In addition, the environmental impacts when considering the potential performance of the mixtures were assessed using a scenario-based analysis. The inventory database was then expanded to include more materials as well as construction processes that could be used to analyze the environmental impacts of various AC and PCC mixtures as well as the work described by pay items used in pavement construction. The cost of the mixtures and pay items were also analyzed to evaluate the cost-effectiveness of implementing common sustainable strategies. Building upon the previous accomplishments, an integrated framework for a roadway/roadside LCA software (rrLCA 1.0) capable of considering drainage, landscape, lighting, pavement, and structural features of a highway infrastructure project was then developed and implemented. Pay items were placed as the building blocks of the software to facilitate agency use of the software, and all applicable life-cycle stages from cradle-to-grave were included.

In the second half of the dissertation, rrLCA 1.0 as well as another airport pavement LCA tool were used to generate and interpret project-level LCA results. A series of 14 diverse acquisition contracts were assessed using rrLCA 1.0, their results were presented in various visualizations and subsequent trends in environmental impacts were discussed in a manner relevant to transportation agencies. A set of sensitivity analyses with these contracts were also undertaken for eight key methodological choices in order to quantitatively determine how the choices affected the overall outcome of the LCA. Finally, the effect of considering secondary data uncertainty was investigated by implementing first a qualitative method of

uncertainty analysis and then a quantitative method of analysis in an airport pavement LCA software. The results of incorporating uncertainty in comparative LCA studies were evaluated in a case study.

7.2 Findings

The major findings of this dissertation are summarized in the three categories below:

7.2.1 Partial LCA outcome

- The energy and GWP associated with producing asphalt mixtures generally decreased with increasing amounts of ABR. In an extreme case, the environmental impacts for a 60% ABR mixture as compared to a virgin mixture were approximately 80% and 78% of the energy and GWP, respectively. An exception to this trend was SMA mixtures which required higher quality aggregates hauled from longer distances, thus reducing or even offsetting the benefits from using recycled materials.
- The additional fuel consumption from pavement roughness over time due to a poor performing HMA overlay can offset environmental savings gained from using recycled materials. The breakeven point representing the pavement service life that results in an equivalent amount of additional fuel energy to energy savings in material production is highly dependent on traffic volume. At high volumes, a small decrease in service life can easily overshadow savings from the material production stage.
- Increased use of common sustainable materials and technologies (i.e., SCMs, RAP, RAS, and WMA) in pavement construction generally reduces environmental impacts from producing and laying pavement, but long hauling distances and modified binders were seen to reduce and even offset environmental benefits.
- A positive relationship between cost and environmental impacts was found for pay items. Higher costs and higher environmental impacts were associated with activities related to upper pavement layers, increasingly lower costs and impacts for lower pavement structures, and the lowest burdens were ultimately seen for preparation activities. Items that had relatively unbalanced cost and environmental impact values could be identified as improvement areas for contractors, producers, and agencies.
- The majority of the commonly employed sustainable strategies evaluated had on average both initial cost and environmental savings while a minority required additional costs to implement environmental savings. This indicated that sustainability strategies may be implemented without economic detriment, assuming equal or better service life.

7.2.2 Project-Level LCA

- A framework for conducting LCA for an entire roadway/roadside system can be implemented consistently using a modular design. A generic LCA procedure can be applied to each roadway/roadside element using similar concepts through material production, construction, maintenance and rehabilitation, use, and EOL. In addition, the use of pay items allows for consistency across modules and most life-cycle stages while also providing a common connection for agencies to incorporate LCA into their acquisition processes.
- A wide range of project types including new construction, reconstruction, widening, and resurfacing projects can be accessed using pavement LCA; however, projects such as ramp reconstruction may have results that are outliers when compared to other projects when using a functional unit based on VMT.
- Project-level LCA results can and should be viewed in different formats to allow for a more holistic interpretation. Impacts can be visualized as total results, results by life-cycle component, detailed project results, and local project results – each provide a unique perspective. In addition to typical energy, GWP, and SS results, LCA outcomes related to transportation intensity, recycled content, and renewable content are noteworthy and relevant to agency sustainability goals.

7.2.3 Sensitivity and uncertainty

- Sensitivity analyses for goal and scope parameters can be used to confirm methodological choices used in LCA by identifying which parameters have a significant impact on the overall results. A cut-off criteria using economic value was appropriate and a cut-off value below the 95%/0.5% would cause significant loss (up to 12% when using a 70% cut-off) of environmental impacts for the M&C stage but less so for the overall lifecycle. Exclusion of infrastructure was shown to result in a significant loss of impacts in the use-phase (up to 61%) and EOL stage (up to 48%) and likely also for the entire lifecycle. EOL allocation using a substitution method has a significant impact (up to 76%) on the M&C, M&R, and EOL stages using a landfill rate of 5% but less likely on the entire lifecycle. Asphalt allocation using various methods has a negligible impact on the overall lifecycle (less than 2%) and a notable impact (up to 6%) on the M&C and M&R stages. Finally, traffic using a non-linear growth rate has a significant (up to 20%) effect on the overall lifecycle impacts.
- LCA choices in the inventory analysis phase also were identified as being significant or not. The use of progressive materials LCIA databases has a notable impact (up to 6%) on the M&C stage but less likely on the entire lifecycle. The use of progressive equipment LCIA databases has a

smaller impact (up to 3.4%) on the M&C stage and thus a negligible effect on the entire lifecycle. The progressive technology LCIA databases incorporating a constant 4% annual emissions reduction in all processes can have a significant impact (up to 50%) on the entire lifecycle. Finally, two-way hauling distances can have a notable impact (up to 5%) on the M&C stage but less likely on the overall lifecycle impacts.

- For impact assessment, it was found that the methodological choice to include primary energy as material results in a significant increase (up to 35%) on the TPE over the pavement life-cycle; however, the gravity of this impact depends on the pavement types considered.
- A DQPM combined with the Monte Carlo method was used to qualitatively assign lognormal distributions to material and construction data in a partial pavement LCA (i.e., only material and initial construction stages). The results showed a distribution of impacts with a mean value similar to the deterministic result.
- Applying an improved BMC method to assign uncertainty to secondary data can significantly alter the distribution of environmental impacts and reduce overall uncertainty in the results. BMC can be used to update prior LCI data based on estimated temporal and regional characteristics using newly observed data generated from open source regression models of normalized CO_2 emissions over time and between countries.
- When a comparative LCA case study for a new runway was performed using various methods (i.e., a deterministic method, a probabilistic method with a DQPM, and a probabilistic method using BMC), the overall conclusion of which alternative design had a greater environmental impact was the same for each but the distribution of results varied significantly among the methods.

7.3 Conclusions

The major conclusions of this dissertation are summarized below:

- Cradle-to-gate environmental analyses of pavement mixtures considering only the materials can quantify immediate environmental benefits or burdens, but this information is incomplete without consideration to the rest of the life-cycle. Environmental impacts from the use-phase can overshadow impacts from the initial lifecycle stages, so it is important for LCA consumers to understand how pavement performance and its resulting implications on fuel consumption over the entire pavement life-cycle can affect initial savings due to materials and construction.
- Cost and environmental impacts from the materials and work required in pay items are positively linked to each other. This relationship should be characterized and utilized for various construction practices, materials, and techniques so that agencies with sustainability goals in both economic and

environmental aspects can make more informed and optimized decisions that will foster benefits from both aspects.

- A comprehensive, appropriate LCA software will allow transportation agencies to assess the environmental impacts of their major construction acquisitions in a meaningful and relevant manner. This software should be based on pay items to allow agencies to more systematically supply the inputs for an LCA. The software should also be able to display results at a granularity that will result in useful interpretations for the agency.
- There are methodological choices in pavement LCA that can significantly affect the outcome of the analysis and some choices that do not significantly affect the analysis. Thus, LCA guidelines should identify choices that are likely to have a large effect on the results and either specify which choices to make or require LCA practitioners to justify and perform sensitivity analyses for key parameters. However, it should also be noted that the significance of certain choices will also be affected by the scope of the LCA (e.g., if the use-phase is included or not).
- The consideration of data uncertainty is critical when performing a comparative LCA for pavement. In addition, the method used to assess uncertainty can significantly shift the distribution of probabilistic results if a biased or informed method is used. Decision makers should be very cautious about comparing alternative designs based solely on deterministic values because the reliability of such comparisons is unknown.

7.4 Recommendations for Future Work

Pavement LCA and its applications is a growing topic of interest that has made great progress in the past few decades, but additional topics remain that can be addressed in future work. Potential areas of research extending from this dissertation include the following:

- While general trends and interpretations were made for project-level results in this study, challenges arose in comparing impacts and characteristics across projects with different traffic levels, dimensions, etc. Future work can evaluate other functional units in addition to those based on dimension or VMT as well as assess use cases for when and how pavement LCA results should be compared. A formal set of guidelines for comparative pavement LCA would aid LCA practitioners in ensuring that LCA consumers and decision makers are interpreting results that are appropriate and comparable.
- The roadway/roadside LCA software described in Chapter 4 of this study was able to include five different elements of the roadway/roadside system; however, only the pavement element was utilized in the case studies. Future work can include analysis of all elements of the

roadway/roadside for construction projects. Issues in compiling results over various elements or comparing relative contributions of each element to the entire system will need to be evaluated in order to ensure that results from all elements are properly represented.

- This study focused on applications and interpretations of pavement LCA from mainly an agency perspective. While transportation agencies are highly affected by this topic, implications of pavement LCA for other stakeholders in the pavement industry as well as for users of the infrastructure can also be evaluated. Thus, research can be expanded to consider how social and economic factors for various affected entities can be integrated with environmental factors through LCA. A more complete picture of sustainability can be drawn by integrating all three components of the triple bottom line.
- Finally, it was acknowledged that the uncertainty analysis performed in Chapter 6 focused on data uncertainty and specifically data quality uncertainty from secondary data. There are many other types of uncertainty that were not addressed in this work, such as that from model and input uncertainty. Future work may expand on the use of uncertainty analysis methods in LCA in order to give LCA consumers the more comprehensive representation of results.

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APPENDIX A

DATA QUALITY PEDIGREE MATRIX (DQPM)

Score:	1	2	3	4	5
U1 Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
	1.00	**1.05**	**1.10**	**1.20**	**1.50**
U2 Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	**1.02**	**1.05**	**1.10**	**1.20**
U3 Temporal correlation	Less than 3 years of difference to our reference year (2000)	Less than 6 years of difference to our reference year (2000)	Less than 10 years of difference to our reference year (2000)	Less than 15 years of difference to our reference year (2000)	Age of data unknown or more than 15 years of difference to our reference year (2000)
	1.00	**1.03**	**1.10**	**1.20**	**1.50**
U4 Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area		Data from unknown OR distinctly different area (north America instead of middle east, OECD-Europe instead of Russia)
	1.00	**1.01**	**1.02**		**1.10**
U5 Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials but same technology, OR Data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00		**1.20**	**1.50**	**2.00**
U6 Sample size	>100, continuous measurement, balance of purchased products	>20	> 10, aggregated figure in environmental report	>=3	unknown
	1.00	**1.02**	**1.05**	**1.10**	**1.20**

Figure A.1: Data quality pedigree matrix used in Ecoinvent (Weidema et al., 2013).