2020

LIFE CYCLE INFORMATION MODELS WITH PARAMETER UNCERTAINTY ANALYSIS TO FACILITATE THE USE OF LIFE-CYCLE ASSESSMENT OUTCOMES IN PAVEMENT DESIGN DECISION-MAKING

Chaitanya Ganesh Bhat
Michigan Technological University, cbhat@mtu.edu

Recommended Citation
Bhat, Chaitanya Ganesh, "LIFE CYCLE INFORMATION MODELS WITH PARAMETER UNCERTAINTY ANALYSIS TO FACILITATE THE USE OF LIFE-CYCLE ASSESSMENT OUTCOMES IN PAVEMENT DESIGN DECISION-MAKING", Open Access Dissertation, Michigan Technological University, 2020.
https://doi.org/10.37099/mtu.dc.etdr/1144

LIFE CYCLE INFORMATION MODELS WITH PARAMETER UNCERTAINTY ANALYSIS TO FACILITATE THE USE OF LIFE-CYCLE ASSESSMENT OUTCOMES IN PAVEMENT DESIGN DECISION-MAKING

By

Chaitanya Ganesh Bhat

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Civil Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2020

This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Civil Engineering.

Department of Civil and Environmental Engineering

Dissertation Advisor:	*Dr. Amlan Mukherjee*
Committee Member:	*Dr. Heather Dylla*
Committee Member:	*Dr. John Harvey*
Committee Member:	*Dr. Jacob Hiller*
Committee Member:	*Dr. Ezra Kahn*
Committee Member:	*Dr. David Shonnard*
Committee Member:	*Dr. Richard Willis*
Committee Member:	*Dr. Zhanping You*
Department Chair	*Dr. Audra Morse*

Table of Contents

List of figures v

List of tables viii

Preface ix

Acknowledgements x

Definitions xi

List of abbreviations xiii

Abstract xiv

1 Chapter 1: Introduction 1
- 1.1 Problem Statement 2
- 1.2 Objectives 3
- 1.3 Research Contribution 4
  - 1.3.1 Academic Contributions 4
  - 1.3.2 Industry Contributions 6
- 1.4 Layout of the Dissertation 7

2 Chapter 2: Background 9
- 2.1 State of the Art for Data Structure Development 11
- 2.2 State of the Art for Uncertainty Analysis 13

3 Chapter 3: Methodology 15
- 3.1 Methodology to Achieve Consistency 15
  - 3.1.1 Pavement LCA Domain Knowledge Representation 16
    - 3.1.1.1 Definition of Process Ontology 17
    - 3.1.1.2 Definition of Lineage Ontology 18
    - 3.1.1.3 Developing Product System Diagrams 19
  - 3.1.2 Development of Baseline Life Cycle Information Models for Pavements 20
    - 3.1.2.1 Development of Data Structures in OpenLCA 21
    - 3.1.2.2 Adding Parameters to The Data Structure 22
    - 3.1.2.3 Mapping to Consistent Background Data 23
- 3.2 Methodology to Achieve Credibility 24
  - 3.2.1 Perturbation of Parameter Uncertainty 25
  - 3.2.2 Background Data Quality 26

3.2.2.1 Flow Level 27
3.2.2.1.1 Reliability of the data 27
3.2.2.1.2 Data Collection Methods 28
3.2.2.1.3 Time Period of Data 29
3.2.2.1.4 Geography of Data 30
3.2.2.1.5 Technology of Data 30
3.2.2.2 Process Level 31
3.2.2.2.1 Process Review 31
3.2.2.2.2 Process Completeness 32

4 Chapter 4: Results 33

4.1 Aleatory Uncertainty 33

4.2 Significance of Equivalence Intervals at Project Level 58

4.3 Applicability of Equivalence Intervals 63

4.4 Epistemic Uncertainty 64

4.5 Protocol (Allocation) Uncertainty 65

5 Conclusions 68

5.1 Concluding Remarks on Life Cycle Information Models 68

5.2 Concluding Remarks on Uncertainty Analysis 69

5.3 Limitations 70

5.4 Scope for Future Research 70
5.4.1 Methodological Opportunities 70
5.4.2 Implementation Opportunities 71

6 Reference List 72
A Fundamental Construct of LCA 77
B Background Data Quality Assessment Results 78
6.1.2 Electricity 78
6.1.3 Natural Gas 79
6.1.4 Diesel 81
6.1.5 Gasoline 84
6.1.6 Liquefied Petroleum Gas 86
6.1.7 Residual Fuel Oil 88
6.1.8 Coal 89
6.1.9 Asphalt Binder 90
6.1.10 End of Life Processes 92

C Copyright documentation 94

List of figures

Figure 1. Classification of Uncertainties for Life Cycle Inventory Data 3

Figure 2. Schematic Workflow to Achieve Consistency 16

Figure 3. Basic Resource Description Schema for Pavement LCA..................................18

Figure 4. Lineage Ontology 19

Figure 5. Mapping Format using Product System Diagrams..20

Figure 6. Hierarchical Data Structure in OpenLCA 22

Figure 7. Glimpse of Parameterized Information Model..23

Figure 8. Potential Stakeholders for Background Data Mapping 24

Figure 9. The Computational Structure for Deterministic LCA as per Heijungs and Suh, (2002) 25

Figure 10. PADD Region Division (Source: EIA) 34

Figure 11. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 1 Foreground Uncertainty in Electricity by Analytical Method..38

Figure 12. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 1 Foreground Uncertainty in Electricity by Monte Carlo Method...39

Figure 13. Sensitivity of GWP (Kg of CO_2 eq) to PADD 1 Foreground Uncertainty in Natural Gas by Analytical Method 40

Figure 14. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 1 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation 41

Figure 15. Sensitivity of GWP (Kg of CO_2 eq) to PADD 2 Foreground Uncertainty in Electricity by Analytical Method..42

Figure 16. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 2 Foreground Uncertainty in Electricity by Monte Carlo Simulation..43

Figure 17. Sensitivity of GWP (Kg of CO_2 eq) to PADD 2 Foreground Uncertainty in Natural Gas by Analytical Method 44

Figure 18. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 2 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation 45

Figure 19. Sensitivity of GWP (Kg of CO_2 eq) to PADD 3 Foreground Uncertainty in Electricity by Analytical Method....46

Figure 20. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 3 Foreground Uncertainty in Electricity by Monte Carlo Simulation....47

Figure 21. Sensitivity of GWP (Kg of CO_2 eq) to PADD 3 Foreground Uncertainty in Natural Gas by Analytical Method....48

Figure 22. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 3 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation....49

Figure 23. Sensitivity of GWP (Kg of CO_2 eq) to PADD 4 Foreground Uncertainty in Electricity by Analytical Method....50

Figure 24. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 4 Foreground Uncertainty in Electricity by Monte Carlo Simulation....51

Figure 25. Sensitivity of GWP (Kg of CO_2 eq) to PADD 4 Foreground Uncertainty in Natural Gas by Analytical Method....52

Figure 26. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 4 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation....53

Figure 27. Sensitivity of GWP (Kg of CO_2 eq) to PADD 5 Foreground Uncertainty in Electricity by Analytical Method....54

Figure 28. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 5 Foreground Uncertainty in Electricity by Monte Carlo Simulation....55

Figure 29. Sensitivity of GWP (Kg of CO_2 eq) to PADD 5 Foreground Uncertainty in Natural Gas by Analytical Method....56

Figure 30. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 5 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation....57

Figure 31. Sensitivity of GWP (Kg of CO_2 eq) to PADD 2 Foreground Uncertainty in Electricity by Analytical Method _ Scaled....59

Figure 32. Sensitivity of GWP (Kg of CO2 eq) to PADD 2 Foreground Uncertainty in Electricity by Monte Carlo Method _ Scaled....60

Figure 33. Sensitivity of GWP (Kg of CO2 eq) to PADD 2 Foreground Uncertainty in Natural Gas by Analytical Method _ Scaled....61

Figure 34. Sensitivity of GWP (Kg of CO2 eq) to PADD 2 Foreground Uncertainty in Natural Gas by Monte Carlo Method _ Scaled....62

Figure 35. Application of Equivalence Intervals 64

Figure 36. Illustration of Epistemic Uncertainty Results..65

Figure 37. Sensitivity to Economic Allocation Factors 67

Figure A.1. 38. Definition of a Product System 77

List of tables

Table 1. Product Flows 35

Table 2. Deterministic LCA Outcomes 35

Table 3. Economic Allocation Coefficients for Asphalt Binder.......................................66

Preface

The dissertation contains the material from the published journal paper listed below (not in its entirety) and from the conference proceeding (not in its entirety) that was initially scheduled in June 2020 but postponed to January 2021 due to COVID-19 complications. In addition, a paper reflecting on the parameterized data models work is currently submitted to the Journal of Transportation Engineering, Part B: Pavements hosted by the ASCE.

1. Bhat, C. and Mukherjee, A., 2019. Sensitivity of Life-Cycle Assessment Outcomes to Parameter Uncertainty: Implications for Material Procurement Decision-Making. *Transportation Research Record: Journal of the Transportation Research Board*, 2673(3), pp.106-114.
2. Bhat, C., Mukherjee, A. and Meijer, J., 2020. Mapping of Unit/Product System Processes for Pavement Life-Cycle Assessment. In: *International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment 2020*.
3. Bhat, C., Mukherjee, A. and Meijer, J. Life Cycle Information Models: Parameterized Linked Data Structures to Facilitate the Consistent Use of Life-Cycle Assessment in Decision-Making. *ASCE, Journal of Transportation Engineering, Part B: Pavements*. *Under Review*.

A holistic assessment of trade-offs between different aspects of sustainability through a framework based approach is presented in the following Journal Paper:

1. Bhat, C. and Mukherjee, A., 2020. Life Cycle Thinking-Informed Approach to Support Pavement Design Decision Making. *Journal of Transportation Engineering, Part B: Pavements*, 146(4), p.04020067.

Acknowledgements

I would like to thank my parents for their continuous support and trust that has contributed immensely towards my professional and personal growth.

I would like to thank my advisor Dr. Amlan Mukherjee for his valuable guidance throughout my master's and Ph.D. program at Michigan Technological University.

I would like to acknowledge the guidance provided by the committee members Dr. John Harvey, Dr. Heather Dylla, Dr. Richard Willis, Dr. Ezra Kahn, Dr. Zhanping You, Dr. David Shonnard, and Dr. Jacob Hiller for their inputs.

I would also like to thank Dr. Ezra Kahn, Dr. Richard Willis, Joep Meijer, research team working on the FHWA LCA tool developed by Applied Pavement Technology for their participation in the collaborative effort that I was part of during my tenure at Michigan Tech.

I would like to thank Engineering & Software Consultants, INC., Federal Highway Administration, National Co-operative Highway Research Program, National Asphalt Pavement Association, Michigan Department of Transportation for their continuous financial support during my master's and Ph.D. program at Michigan Technological University.

I would like to thank Dr. Richard Willis, Joseph Shacat and Brett Williams from National Asphalt Pavement Association for providing an opportunity to intern during the summer of 2018 and allowing me to use the data to conduct the analysis presented in this dissertation.

I would like to thank Michigan Department of Transportation, National Co-Operative Highway Research program, Federal Highway Administration to fund my research under contract # DTFH6117D00005 awarded to Engineering & Software Consultants, Inc. (ESCINC) and hosted by the Michigan Tech Transportation Institute under a subcontract from ESCINC.

Finally, I would like to thank my colleagues and administrative staff at Michigan Tech for their professional and personal support at all times.

Definitions

Transparency: Open, comprehensive and understandable presentation of information (ISO 14044 2006, 3.7)

Product: Any good or service (ISO 14044 2006, 3.9)

Raw Material: Primary or secondary material that is used to produce a product (ISO 14044 2006, 3.15)

Elementary flow: (1) Material and energy entering the system being studied that has been drawn from the environment without previous human transformation

(2) Material or energy leaving the system being studied that is released into the environment without subsequent human transformation (ISO 14044 2006, 3.12)

Releases: Emissions to air and discharges to water and soil (ISO 14040 2006, 3.30)

Waste: Substances or objects which the holder intends or required to dispose of (ISO 14040 2006, 3.35)

Life cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO 14044 2006, 3.1)

Life-cycle assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14044 2006, 3.2)

Life-cycle inventory analysis: Phase of life-cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14044 2006, 3.3)

Unit process: Smallest element considered in the life-cycle inventory analysis for which input, and output data are quantified (ISO 14044 2006, 3.34)

Input: Product, material or energy flow that enters a unit process (ISO 14044 2006, 3.21)

Output: Product, material or energy flow that leaves a unit process (ISO 14044 2006, 3.25)

Product system: Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product (ISO 14044 2006, 3.28)

Life-cycle impact assessment: Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 14044 2006, 3.4)

Product flow: Products entering from or leaving to another product system (ISO 14044 2006, 3.27)

System boundary: Set of criteria specifying which unit processes are part of a product system (ISO 14044 2006, 3.32)

Co-Product: Ant two or more products coming from the same unit process or product system (ISO 14040 2006, 3.10)

Allocation: 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 (ISO 14044 2006, 3.17)

Cut-off criteria: Specification of 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 (ISO 14044 2006, 3.18)

Data Quality: Characteristics of data that relate to their ability to satisfy stated requirements (ISO 14044 2006, 3.19)

List of abbreviations

ANL	Argonne National Lab
API	Application Programming Interface
DOT	Department of Transportation
EPD	Environmental Product Declaration
FHWA	Federal Highway Administration
GWP	Global Warming Potential
HMA	Hot-Mix Asphalt
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life-cycle Impact Assessment
LCIM	Life Cycle Information Models
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
PCR	Product Category Rule
RAP	Reclaimed Asphalt pavement
RDF	Resource Description Framework
SPTWG	Sustainable Pavements Technical Working Group
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency

Abstract

The objective of this dissertation is to develop Life Cycle Information Models (LCIMs) to promote consistent and credible communication of potential environmental impacts quantified through Life-Cycle Assessment (LCA) methodology. The introduction of Life Cycle Information Models (LCIMs) will shift the focus of pavement LCA stakeholders to collect reliable foreground data and adapt to consistent background data present within LCIMs. LCA methodology requires significant Life Cycle Inventory (LCI) data to model real world systems and quantify potential environmental impacts. The lack of guidance in ISO standards on consistently compiling LCI data and defining protocols for modeling lowers the reliability of LCA outcomes. In addition, LCA outcomes are communicated as point estimates despite the variations associated with input data. These limitations provided two motivations for this dissertation. The first motivation is to develop an information modeling approach to support the formal specification of relationships between pavement LCA flows and processes, while mapping them to a consistent set of background LCI and foreground process parameters. The second motivation is to develop the margins of error within LCA outcomes by propagating different types of uncertainties. An illustration of the discussed methodology is provided for the case of Hot-Mix Asphalt (HMA) mixtures containing varying amounts of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS). LCIMs serve as a building block for a complete LCA and formalizing the underlying model and upstream datasets. This builds trust among pavement LCA stakeholders by promoting the use of consistent underlying relationships between unit product systems, processes, and flows within pavement LCA system boundary and mapping them to consistent, transparent public background datasets. Pavement LCA stakeholders are empowered to develop context-specific LCA outcomes using LCIMs and can reliably incorporate these outcomes within decision-making by highlighting the margins of error associated with the results. The methodology discussed in this dissertation is timely with emerging legislations such as the Buy Clean Act (2017) in California that requires highway construction contractors to produce LCA based Environmental Product Declarations (EPDs), at the point of installation, for a list of all eligible construction materials.

1 Chapter 1: Introduction

The transportation sector in the United States contributes to 29 percent of greenhouse gas emissions (US EPA, 2019). As the pressures of climate change are mounting, there has been a growing emphasis on the environmental sustainability of the supply chain used to design, construct and maintain transportation infrastructure. The first step to achieve environmental sustainability is to estimate the current environmental impacts for establishing reference baselines. The reference baselines can then be used to assess the effectiveness of new strategies to reduce impacts. The potential environmental impacts can be quantified using Life-Cycle Assessment (LCA) for which the principles and framework are provided in the International Organization for Standardization (ISO) Standard 14040 (ISO, 2006a) and requirements and guidelines are provided in the ISO Standard 14044 (ISO, 2006b).

LCA methodology requires significant LCI data to completely represent the supply chain of a product. For example, to quantify environmental impacts from asphalt mixture production at a plant, different levels of LCI data would be required. The first level of data would include the quantified values for materials (aggregates, asphalt binder, etc.) and energies (renewable and/or non-renewable) used at a plant. The next level of data will include environmental impacts due to the production of these different materials and energies. To explicitly differentiate the levels of data, this dissertation defines two different kinds of LCI data (Mukherjee, Bhat and Harvey, 2020):

1. Foreground: data that is specific to pavement LCA and a pavement LCA practitioner has direct control over it through modification of design and construction strategies. For example, the percentage of recycled content in the pavement, or the quantity of diesel used by equipment during construction, or the distance traveled through transportation are examples for foreground data.
2. Background: The plant manager would not have control over the amount of renewable and non-renewable energy sources used for the generation of electricity that is used as an energy source at the plant. Also, the plant manager would not have control over the amount of energy used in the production of an upstream material such as aggregate. This would be "background data" for the LCA practitioner. In general, background data is the data that is characterized by generic public inventories, and the LCA practitioner has no influence on it and does not directly measure it.

In order to meet the requirements of the plant manager i.e. to quantify the environmental impacts from the production of "x" quantity of asphalt mixture, the LCA practitioner needs to account for the foreground, and the background data.

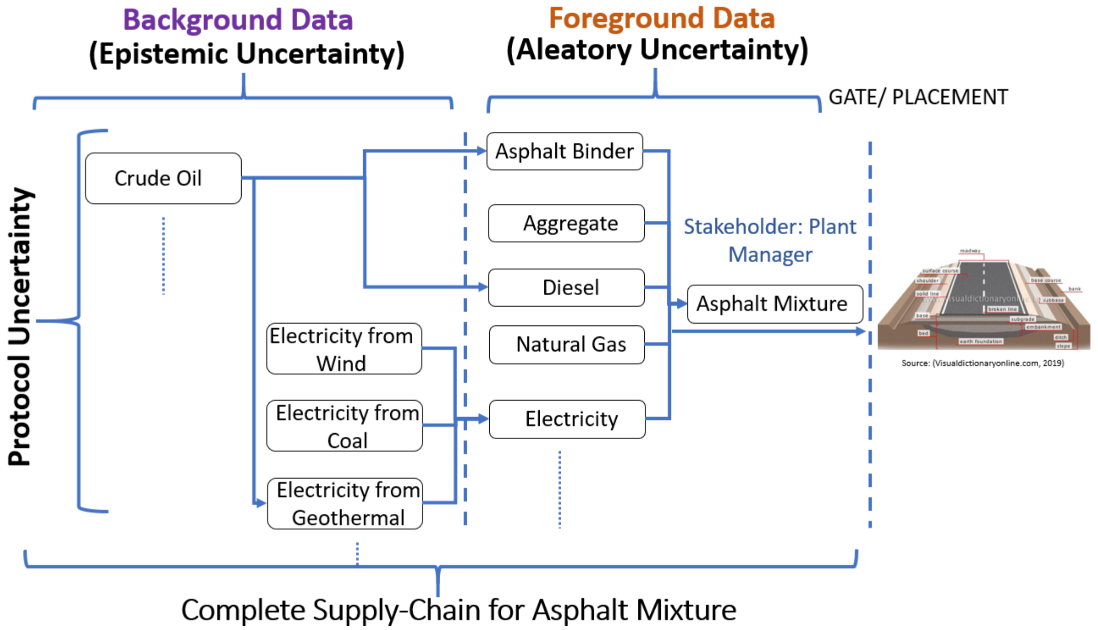
The use of LCAs has gained importance within the pavement community with the recent enactment of the Buy Clean Act (2017) in California. This act requires highway construction contractors, at the point of installation, to produce an Environmental Product Declarations (EPDs) for a list of all eligible construction materials. Type III EPDs communicate independently verified potential life-cycle environmental impacts of a product or service using methods in LCA. They are governed by ISO Standards 14025 (ISO, 2006c) and 21930 (ISO, 2017). Legislation in California is the first instance in the United States where LCA outcomes have been required in public procurement. Even though, at this time the EPD information being collected is only being used for benchmarking purposes, in future, it is intended to support decision-making.

1.1 Problem Statement

The lack of detailed guidance on compiling background LCI data in ISO Standards has led to the development of numerous LCA studies producing incomparable outcomes (Ingwersen and Stevenson, 2012). These LCA outcomes may not be feasible to support decision-making or to identify strategies to reduce climate change. For example, it may not be feasible to compare the LCA outcomes from the production of one ton of concrete mixtures at two nearby plants if the LCA study employs background electricity data using a 'European grid-mix' for one plant and a 'United States average grid-mix' for the other. The 'European grid-mix' data may not be comparable to the 'U.S. average grid-mix' data due to the different proportions of renewable and non-renewable energy sources used for electricity production. The incomparability of LCA outcomes due to the use of different background data calls for the consistent use of LCI data and becomes the first objective of this research. The term "*consistency*" refers to the use of datasets and protocols representing the same geography, technology and system boundaries in conducting a comparative LCA, when used to support decision-making. Consistency is particularly important in pavement construction as competing construction materials like aggregate, asphalt, concrete and steel share supply chains, and common upstream energy sources and transportation modes.

The conformance to consistency alone does not guarantee the credible communication of LCA outcomes. This is because, despite the variations in input LCI data, the environmental impacts of products and processes are typically communicated as point estimates (Mendoza Beltran et al., 2018). For example, the foreground data for electricity and energy used for asphalt mixture production may vary based on the geographical location of a plant (Mukherjee, 2016) and hence, the LCA outcomes for asphalt mixtures need to be communicated with margins of error. This becomes the second objective of this research that aims to credibly communicate LCA outcomes. The term "*credibility*" refers to the correctness of LCA outcomes used for comparing different products. Some of the contributing factors for the variation or the uncertainty in input LCI data include inherent variations in the data and choices made by an LCA practitioner for an LCA study. The selection of a methodology to propagate uncertainty depends on the availability of data on uncertainty as well as computational efficiencies.

The uncertainties that may occur within different types of life-cycle inventory data have been presented for the case of asphalt mixture production in Figure 1. Foreground data uncertainties may be due to diurnal variations in the measured or estimated quantities of material or energy at an asphalt plant and hence fall within aleatory uncertainty or uncertainty due to inherent randomness. Background data uncertainties may be due to the selection of data from a different geography or using different technology than those mentioned within the scope of an LCA study. The uncertainties due to background data fall within epistemic uncertainty or uncertainty due to lack of knowledge. Uncertainties may also occur due to assumptions related to LCA protocols such as allocation of upstream environmental impacts from crude oil refining to different products. Hence, it is important to account for aleatory, epistemic and protocol uncertainties for credible communication of LCA outcomes.



Source: (Visualdictionaryonline.com, 2019)

Figure 1. Classification of Uncertainties for Life Cycle Inventory Data

The classification of foreground and background data to aleatory and epistemic uncertainties respectively is done with respect to the context of this dissertation. However, it should be noted that background data might also have aleatory uncertainty associated with them e.g., if consumption-based electricity is used to complete the supply chain of a product, the total energy consumption or Global Warming Potential (GWP) from electricity may include aleatory uncertainties due to variation in the consumption of electricity based on the time of the day and the sources generating the electricity.

1.2 Objectives

The drawbacks identified in the problem statement section formulate the following objectives for the research presented in this dissertation:

1. **Ensure Consistency:** Develop an ontology-driven reusable and extensible life cycle information models in an open-source environment to represent semantic and syntactic heredity for pavements and ensure the use of consistent LCI data

2. **Ensure Credibility:** Propagate aleatory, epistemic and protocol uncertainties and communicate Life-Cycle Impact Assessment (LCIA) outcomes with margins of error instead of point estimates

The conformance of consistency alone does not guarantee credible communication of LCA outcomes and hence, the LCA outcomes need to be communicated with margins of error to account for variations in LCI data.

1.3 Research Contribution

The research discussed in this dissertation is motivated by the need for a standard specification of datasets, products and processes for pavement LCA to ensure transparency and verifiable quality of background Life Cycle Inventories (LCI). In addition, the research focuses on credible communication of potential environmental impacts by incorporating different kinds of uncertainties within the LCI data. The specific contributions of this dissertation are:

1. Develops a formalism through an ontology-based approach to specify the relationships between pavement LCA flows and processes.
2. The data structures are also mapped onto background LCI, and foreground parameters that are used in pavement LCA, to create parametric information models that we refer to as Life Cycle Information Models (LCIM), and the LCIMs can be used "building blocks" for pavement LCA.
3. As LCA software tools are developed to support decision-making for departments of transportation, the ontological representation of the pavement domain can serve as a specification outlining a common set of protocols.
4. Develops equivalence intervals due to aleatory uncertainty and examines the sensitivity due to epistemic and protocol uncertainties for alternative asphalt mixtures.
5. Develops a data quality assessment method based on USEPA's updated pedigree matrix approach (Edelen and Ingwersen, 2016) and illustrates the method for common public background data categories

The following sections detail the specific contributions to academia and industry from the research presented in this dissertation:

1.3.1 Academic Contributions

The academic contributions from the dissertation include the development of LCIMs that provides a pathway to move towards the development of consistent context-specific digital LCA models. The ontology for LCIMs discussed in the dissertation details the unit product system/processes within the pavement LCA system boundary and maps them to consistent public background datasets. The parametric LCIMs convert the raw data into useful for asphalt mixtures at this time, however, can be extended to other product systems as well.

The introduction of Life Cycle Information Models (LCIMs) can empower pavement LCA stakeholders to collect reliable foreground data and take advantage of consistent background data present within LCIMs. LCIMs serve as a building block for a complete pavement LCA by formalizing the underlying model and upstream datasets. For example, the LCIMs for asphalt mixtures discussed in this dissertation may be used as a building block for quantifying the environmental impacts from a construction or maintenance activity that uses asphalt mixture.

LCIMs build trust among pavement LCA stakeholders by promoting the use of consistent underlying relationships between unit product systems, processes, and flows within pavement LCA system boundary and mapping them to consistent, transparent public background datasets. This empowers pavement LCA stakeholders to develop context-specific LCA outcomes using LCIMs and shifts their focus towards collecting empirical data and statistically characterizing distributions that adequately represent foreground data. For example, hot in-place recycling activities such as repaving or remixing are employed on a pavement to correct surface distresses. Using LCIMs a decision maker at a state department of transportation can focus on the collection of statistically characterized foreground parameters such as different amounts of fuel combusted in a construction equipment or the varying transportation distances associated with these equipment and rely on LCIMs to consistently map the background data for the upstream impacts from the extraction of fossil fuels and materials within LCIMs.

The dissertation also illustrates the concept of equivalence intervals due to aleatory uncertainty and examines the sensitivity due to epistemic and protocol uncertainties for Hot-Mix Asphalt (HMA) mixtures with varying amounts of Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS). The equivalence interval refers to the range of Global Warming Potential (GWP) for which the savings in the GWP because of higher RAP, RAS use may be discounted due to the variation in electricity and energy consumption. The equivalence intervals are developed using the variations in input data for electricity and energy from Mukherjee, (2016) and analytical approach developed by Heijungs and Suh, (2002) as well as using Monte Carlo Simulation in the OpenLCA software. The equivalence intervals provide an insight on whether the range of potential environmental impacts are an artifact of a methodology applied to propagate uncertainty or the availability of foreground data with confidence intervals. In addition, the dissertation discusses the margins of error due to epistemic and protocol uncertainties specifically allocation uncertainties.

The dissertation discusses a pavement specific pedigree matrix that aids the pavement LCA stakeholders to consistently assess the data quality of both the foreground and background data. The dissertation also illustrates the matrix for the public background data categories and provides an insight to both the background data providers on scope for improvement and to downstream pavement LCA stakeholders on selecting specific background datasets.

1.3.2 Industry Contributions

The industry contributions from the dissertation include the open source ontology highlighting consistent unit product system/processes within the pavement LCA system boundary that provides a starting point to develop both pavement and LCA domain specific rules and facilitate automated workflow to achieve sustainability. The LCIMs developed for asphalt mixtures will be used to collect foreground parameters and conduct LCA to support the Product Category Rules (PCRs) for Environmental Product Declarations (EPDs) program hosted by the National Asphalt Pavement Association (NAPA). The life cycle impact assessment results and energy indicators calculated for the common public background data from LCA Commons along with the data quality assessment results are communicated with the pavement LCA tool funded by the Federal Highway Administration developed by the Applied Pavement Technology.

In addition, the LCIMs will serve as the platform to conduct context-specific LCIs and assess the sensitivity of selecting different background data for the case studies with the Arizona department of transportation and Illinois Tollway respectively. The approach used for developing Life Cycle Information Models (LCIMs) is communicated with TriSight Engineering that believes in data driven communication of sustainable practices and Building Transparency, a non-profit organization with a core mission to provide open access data and tools that intends to leverage on the status quo of LCIMs and further it for other pavement materials to generate Environmental Product Declarations (EPDs).

In a related effort, a Product Category Rule (PCR) guidance and a background data roadmap are developed as a part of the Federal Highway Administration (FHWA) funded "Roadmap for Background Data and PCR Guidance" under contract # DTFH6117D00005 awarded to Engineering & Software Consultants, Inc. (ESCINC) and hosted by the Michigan Tech Transportation Institute under a subcontract from ESCINC.

The knowledge developed in the course of Ph.D. was disseminated through following conference presentations and workshops:

1. From Trade-Offs to Equivalent Solutions: A Life Cycle Thinking Informed Approach to Design Decision Making at the *97th Annual Transportation Research Board Meeting*, Washington D.C
2. Mapping of Unit Product System/Processes for Pavement Life-Cycle Assessment at the *International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment 2020 (Rescheduled to Jan 2021)*, Sacramento, California
3. Technical and Organizational Challenges to Developing Product Category Rules for Asphalt Pavement Construction at the *International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment 2020 (Rescheduled to Jan 2021),* Sacramento, California
4. Harmonization of Product Category Rules for Highway Construction Materials. In: *American Center for Life Cycle Assessment*., 24th September 2020 as well as for Highway Construction Stakeholders on March 16th, 2020.

The journal papers published and in review are mentioned in the preface.

1.4 Layout of the Dissertation

Chapter 1 Introduction

This chapter lays out the context of the dissertation by identifying the constrains for reliable inclusion of LCA outcomes within decision-making, defines the objectives to overcome these constrains and discusses the research contributions from this dissertation.

Chapter 2 Background

This chapter identifies the existing work on pavement LCA domain by stakeholders within the Federal Highway Administrations (FHWA)'s Sustainable Pavements Technical Working Group (SPTWG). In addition, the chapter identifies the points of departure to achieve the objectives of consistency and credibility by studying the status quo on the development of data structures from other domains and the state of the art to propagate parameter uncertainty within life cycle inventory data respectively.

Chapter 3 Methodology

This chapter discusses the development of a formalism through an ontology-based approach to specify the relationships between pavement LCA flows and processes, mapping of data structures onto consistent background LCI and foreground parameters that are used in pavement LCA, to create parametric information models that we refer to as Life Cycle Information Models (LCIM). LCIMs can be used "building blocks" for pavement LCA. The chapter also discusses an analytical approach coined by Heijungs and Suh, (2002) to propagate parameter uncertainty within life cycle impact assessment outcomes due to diurnal variations within the life cycle inventory data. Lastly, the chapter discusses a pavement-specific pedigree matrix approach developed based on the USEPA's updated pedigree matrix (Edelen and Ingwersen, 2016) to assess the quality of both the foreground and the background data.

Chapter 4 Results

This chapter discusses the variation in the life cycle impact assessment outcomes (specifically Global Warming Potential(GWP)) due to three types of uncertainties, namely:

1. Aleatory uncertainty: developing equivalence intervals for alternative hot-mix asphalt mixtures containing varying amounts of RAP and RAS using both the analytical approach by Hejungs and Suh, (2002) and Monte Carlo simulations
2. Epistemic uncertainty: assessing the sensitivity of GWP due to selection of different background data for asphalt binder and electricity

3. Protocol uncertainty: assessing the sensitivity of GWP due to variation in the economic allocation factors for crude oil refinery outputs across different Petroleum Administration Defense Districts (PADD) regions.

Chapter 5 Conclusions and Scope for Future Work

This chapter discusses the research contributions from the dissertation to achieve the objectives of consistency and credibility. In addition, the limitations associated with the dissertation are discussed along with the scope for future research to overcome these limitations.

2 Chapter 2: Background

Pavements are constructed using various combinations of materials such as concrete, asphalt, steel, and aggregate to serve a wide range of functionalities. The production of these materials contribute to global greenhouse gas emissions [(Ma et al. 2016), (Chehovits and Galehouse 2010)], a primary contributor to Global Warming Potential (GWP). Life-Cycle Assessment (LCA) methodology is used to quantify potential environmental impacts in compliance with the framework and principles provided in the ISO Standard 14040 and requirements and guidelines provided in the ISO Standard 14044. The Federal Highway Administration's (FHWA) Sustainable Pavements Program (SPP) (Sustainable Pavement Program - Sustainability - Pavements - Federal Highway Administration, 2019) and the associated Sustainable Pavements Technical Working Group (SPTWG) have produced the pavement sustainability reference manual (Van Dam et al., 2015) and the pavement LCA framework (Harvey et al., 2016). The pavement sustainability reference manual provides a listing of entities within the pavement domain from the perspective of different sustainability aspects such as performance criteria, environmental impacts, cost, and social impacts. The pavement LCA framework defines an explicit relationship between the principles of the LCA domain and the entities within the pavement domain. These are foundational resources for state and federal agencies to develop a better understanding of pavement LCA and its relationship to building sustainable pavements.

The pavement construction materials industry has embraced the use of LCA, and each of the pavement construction materials is identified as a product category and has accompanying Product Category Rules (PCRs) (Mukherjee, Bhat and Harvey, 2020) that are compliant with ISO Standards 14025 (ISO, 2006a), 14040 (ISO, 2006b) and 14044 (ISO, 2006c) and EN Standard 15804 (EN 15804: Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products | U.S. Green Building Council, 2012). PCRs specify the requirements for modeling the product system, unit processes to include, life-cycle inventory data to use, life-cycle impact assessment indicators to be included when LCA outcomes are used as a basis for an Environmental Product Declaration (EPD) (Del Borghi 2012). These additional category-specific rules are meant to assist in the development of declarations or labels for products that are comparable (Ingwersen and Stevenson 2012). The environmental impacts communicated through a Type III EPDs is different than just LCA outcomes in a way that the latter is based on rules defined within the study by the authors (Ingwersen and Stevenson 2012) and the former is third-party verified information intended to provide consistent, complete, transparent and trustworthy information (Gelowitz and McArthur 2017).

Meanwhile, industry efforts in developing EPD programs have been supported by and conducted in collaboration with the ongoing academic inquiry (Mukherjee, 2016) involving models of the use stage of pavement LCA, with emphasis on topics such as Pavement-Vehicle Interaction (PVI) [(Pavement Vehicle Interaction (PVI) | Concrete Sustainability Hub, 2019), (Zaabar and Chatti, 2010), (Harvey et al., 2015)] and heat island effect [(Sen and Roesler, (2016), Li, (2012)].

Despite these advancements, The FHWA effort falls short of providing a formal digital specification that can be reproduced reliably across different construction materials and process system boundaries to ensure consistency in pavement LCA. While data quality assurance standards are outlined in ISO Standard 14044 (ISO, 2006b) and EN Standard 15804 (EN 15804: Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products | U.S. Green Building Council, 2012) and can be used to check for the compliance of the datasets being used to conduct LCA, there is a limited specification of the background and foreground LCI data that should be used. In addition, there are inconsistencies in the use of LCI for shared background flows in EPDs across different unharmonized PCRs. This has led to inconsistent development of EPDs as there are no controls limiting the use of different background LCI even when they are compliant with the same PCR (Ingwersen and Stevenson, 2012).

In addition to the inconsistent use of background LCI data, the conventional LCA studies communicate point estimates of environmental impacts without defining margins of error (Mendoza Beltran et al., 2018). This lowers the credibility of using LCA in the decision-making process – especially when comparing alternative that has different sources of uncertainty in their material and energy flows. This is because, the values for environmental impacts communicated through LCA implicitly includes aleatory (due to inherent randomness), epistemic (due to lack of knowledge) and protocol uncertainties (presented in Figure 1), even though they are not explicitly considered or communicated. This creates an ambiguity in deciding the relative ranking of different alternatives. Even under the fairest of conditions knowing the significance of a difference between two options can be difficult. For instance, if the acceptable error margins for benchmarking GWP for two options of equivalent functionality are +/-***X%*** and +/-***Y%*** respectively, then for some overlap of the ranges that is a function of ***X%*** and ***Y%***, the options should be considered to have an effectively equivalent impact (Bhat and Mukherjee, 2019).

The specific gaps identified from the state of the art for pavement LCA are:

1. Lack of data-driven models for semantic and syntactic knowledge representation and management of pavement domain from an LCA perspective
2. Inconsistent use of data from various domains neglecting their diverse sources and spatial-temporal variations
3. Limited accounting of uncertainty in input data without reflecting the margins of error for LCA outcomes

The next two sections discuss the state of the art for ontology to counter the problem of inconsistency and state of the art for uncertainty to identify methods to enhance the credibility of LCA outcomes respectively.

2.1 State of the Art for Data Structure Development

Methodologically, the primary points of departure for the development of data structure are in the field considering the use of standardized and structured LCA data and models. The manufacturing industry's digitalized approach towards LCA provides useful insights for pavement LCA. A recent effort (Bernstein, Tamayo, Lechevalier and Brundage, 2019) mapped data formats for Unit Manufacturing Process (UMP) models as defined by ASTM Standard E3012, (2016) with the data format for Ecospold (gmbH, 2019), used for compiling an LCI. While the approach towards LCA application by the manufacturing industry provides direction for the pavement industry, as of now there are no open platforms to facilitate the mapping of explicit design data models required to conduct a product specific LCA. As a result, the pavement domain-specific knowledge representation, management, and sharing is limited, and mapping of LCI models with the data models for other aspects of sustainability such as performance and cost cannot be evaluated across different system platforms (Villa, Athanasiadis and Rizzoli, 2009). This provides a point of departure highlighting the need to develop an abstract and simplified representation of pavement LCA domain knowledge based on the FHWA framework. An ontology based approach may be used to develop an abstract representation for the pavement LCA domain to support the development of data models.

An ontology is a formal data structure that provides an explanation about the concepts and relationships between different concepts within a domain using standardized ways such as a Resource Description Framework (RDF) (Wand, Storey and Weber, 1999). The term ontology originated in philosophy where it is referred to as a systematic account of existence (Gruber, 1993). In the context of the pavement LCA domain, ontology is intended to provide a relational grammar that can be used to represent interactions between flows and processes as defined within the pavement LCA framework. The ontology development for pavement LCA builds on methods in literature that define ontologies for LCA in other fields. Janowicz et al., (2015) presented a minimal ontology pattern for the core semantic description of key elements within LCA. Their ontology aimed to foster interoperability between existing data models, specifications and software given the inter-disciplinary and granular nature of data collection required for LCA. They specified the notions and properties of flows, activities, agents, and products with an intention to reduce the inefficiencies in LCA data collection and management for commonly used chemicals (Janowicz et al., 2015). Ingwersen et al., (2015) initiated the development of an LCA Harmonization Tool (LCA-HT), using the RDF format and defined a new data architecture for chemicals. The purpose of their study was to enhance the data interoperability by automatically combining, storing, and annotating LCA data. Cashman et al., (2016) identified challenges in data management practices and developed a data mining method based on lineage and process ontologies. Further, they initiated the automation of data inventory modeling. Their work encouraged the use of publicly available data at the United States Environmental Protection Agency (USEPA) in the field of chemical manufacturing. Edelen et al., (2017) identified the gaps in the existing definition of elementary flows (representative of direct interactions with the environment) and proposed an approach to benchmark the collection, definition, and evaluation of data through typology, use of unique identifiers and standard nomenclature. Zhang et al., (2015) developed flow and process ontologies using the Web Ontology Language, followed by a semantic representation model to present the relationships between flows and processes as an RDF graph.

Points of departure for the development of data structure:

Based on a summary of this body of research, the following representational constructs provide the foundation for the ontology proposed in this dissertation.

- The use of RDF for relating entities such as flows and processes in a subject-predicate-object relationship within the context of a product system per Ingwersen et al., (2015).
- The use of a set parameter typology for each entity that is being mapped as per Edelen et al., (2017). This helps to specify the parameters that are provided as input by pavement engineers and other stakeholders in conducting LCA.
- The use of lineage and process ontologies, as used by Cashman et al., (2016) in organizing and relating the generic relationships between LCA entities such as flows and processes, and the specific relationships between materials, energy, and processes used that are specific to the product system at hand. This provides the underlying structure for the ontology that can reflect the RDF relationships.
- Adoption of an object-oriented approach to associate the parameter typology for a product system to the underlying ontology framework. As the OpenLCA Application Programming Interface (API) (GreenDelta/olca-modules, 2020) already has a set of class definitions in place for critical entities representing flows, processes, and product systems; a decision was made to inherit their class definitions.

The above elements provide the points of departure to achieve the objective of consistency.

A critical difference between the discussed literature and the ontology developed in this dissertation for mapping pavement LCA unit product systems/processes, is the underlying motivation. For example, Zhang et al., (2015)'s work is motivated by the need to develop deductive reasoning approaches to automate the model for LCA. They implemented the model for a case study of ball bearings. Similarly, Cashman et al., (2016) used data mining to infer a framework of relationships that reflected inventory models in the chemical manufacturing industry. In comparison, rather than use the ontology to make discoveries about the structure of the pavement domain, this dissertation builds on the existing pavement LCA framework to define a standard representation of product and process relationships as a foundational component for developing LCIMs. It is expected that such models can prove to be LCA "building blocks" that will improve standardize the LCA modeling process, shifting the burden of work to collecting high quality process data as required by the specified parameters. In turn this will improve the reliability of the LCA results. The ontology itself has the potential of becoming the cornerstone of an LCA specification akin to a PCR, explicitly defining system boundaries, relationships, and assumptions that may influence the outcome of an EPD.

2.2 State of the Art for Uncertainty Analysis

Uncertainty is defined as the discrepancy between a measured quantity or a calculated quantity and the true value of that quantity (Finnveden et al., 2009). ISO Standard 14044 recommends an LCA practitioner to conduct both sensitivity and uncertainty analysis while disclosing the results to the public for a comparative study. However, the Standard does not provide any methodological guidance on these processes (Gregory et al., 2016). The lack of consideration of uncertainty in an LCA process can be attributed to its complex nature. This creates an ambiguity in deciding the relative ranking of different alternatives (Ciroth, 2004). Morgan and Henrion, (2007) listed seven quantities that cause uncertainty in the context of risk and policy analysis namely, empirical parameter or chance variable, defined constant, decision variable, value parameter, index variable, model domain parameter and, outcome criterion. Gregory et al., (2016) furthered this body of knowledge by specifying these causes for the case of LCA and suggested methods for analyzing uncertainty for a specific type and cause of uncertainty.

Uncertainties in an LCA are caused by the following reasons (Wei et al., 2016):

1. Temporal and geographic uncertainty in the LCI data
2. Uncertainty due to the assumptions and choices while computing an LCA model
3. Underlying computational uncertainties during LCA calculation and,
4. Uncertainties in the characterization models used for LCIA

Huijbregts et al., (2003) further condense these sources into three categories:

1. Parameter uncertainty: uncertainty in the observed or measured value of a parameter
2. Scenario uncertainty: uncertainty due to normative choices made by a practitioner and,
3. Model uncertainty: uncertainty due to the structure and mathematical relationships within a model.

Llyod and Ries, (2007) detailed different sources causing uncertainty under each parameter, scenario, and model uncertainty. They also listed the different methods used by previous studies to propagate these uncertainties: stochastic modeling, scenario modeling, fuzzy data sets, analytical uncertainty propagation, and Bayesian statistics. Specifically, parameter uncertainty can be propagated through either analytical methods or stochastic methods. However, this selection is ambiguous as there is no recommendation of a methodology for a specific goal and scope of an LCA. The advantage of analytical methods over stochastic methods is that they can be applied in case of limited knowledge about the uncertainty in the input data. Specifically, in the case of analytical methods, there is no need for a complete probability distribution to characterize the uncertainty of input parameters and second moments such as standard deviation, variance, and coefficient of variation is enough to propagate uncertainty. Also, analytical methods do not require considerations of computational efficiency as some of the stochastic methods such as Monte Carlo Simulation do. A disadvantage of the analytical method is that formulating the matrices with a large number of input parameters can be tedious and difficult to scale for a large number of parameters. Hence, the choice of the method used should be based on the particulars of the study.

Particularly in pavement LCAs, there has been significant research on propagating both parameter, and scenario uncertainty using stochastic methods such as Monte Carlo simulation. Noshavardhan et al., (2013) compared the environmental impacts between asphalt and concrete pavements for all life-cycle stages by propagating the parameter uncertainty, including correlations between input parameters. They estimated the variance in LCA outcomes due to parameter uncertainty by adding uncertainty in foreground data (measurement uncertainty based on estimates for input data) using Monte Carlo simulation and background data (data-quality uncertainty) using data-quality indicators established by Ecoinvent. Gregory et al., (2017) proposed a methodology for robust comparison of pavement alternatives based on LCA outcomes considering both parameter and scenario uncertainties. Their methodology included a combination of probabilistic-scenario analysis to propagate uncertainty and influential parameter selection to interpret the environmentally sustainable alternative.

Points of departure for dissertation

The state of the art for data structure development and uncertainty analysis provide the following points of departure for this dissertation:

1. It is critical that there is transparency in choice and verifiable quality of background LCI. If these needs are not met, in the long run, they may hinder the incorporation of LCA and EPDs in the policy arena – particularly in the context of public procurement. Hence, the point of departure to achieve the objective of consistency is to develop Life Cycle Information Models (LCIMs) that layout standard specification of datasets, products and processes for pavement LCA and mapped to consistent public background LCI and foreground parameters. LCIMs can also be used to determine the margins of error in LCA outcomes due to the selection of different background datasets for a product system.
2. There is a lack of homogeneity in the classification of uncertainties and listing of the sources causing these uncertainties in LCA. Also, there is a limited discussion on the relative ranking of these uncertainties and there is no benchmarking of appropriate methods to propagate the uncertainties through an LCA study (Llyod and Ries, 2007). Hence, the point of departure to achieve the objective of credibility is to propagate uncertainty using both the analytical method as well as stochastic methods. This will provide an insight on whether the margins of error in LCA outcomes are due to the methodology used to propagate uncertainty or the LCI data itself. In addition, there is a need to consistently assess the data quality of common public background data categories used within pavement LCA system boundary.

3 Chapter 3: Methodology

This chapter discusses the methodologies to achieve the objectives of consistency and credibility. Consistency is achieved by proposing a formalism to specify the relationships between pavement LCA flows and processes, while mapping them to a consistent set of background LCI and foreground parameters. Credibility is achieved by first discussing an analytical method developed by Heijungs and Suh, (2002) to propagate parameter uncertainty and develop margins of error between alternatives. Second, a pavement-specific pedigree matrix is discussed to consistently assess the data quality of common background data categories from LCA Commons.

3.1 Methodology to Achieve Consistency

The methodological underpinning to achieve the objective of consistency is based on a merger of modern knowledge representation theory along with the rationale of declarative modeling (Villa, Athanasiadis and Rizzoli, 2009) to represent the pavement LCA framework. The methodology to consistently represent and model the pavement LCA framework can be divided into following steps:

i. Develop an ontology to represent the unit product system/processes relevant within the pavement LCA system boundary
ii. Develop the Life Cycle Information Models (LCIMs) using a linked hierarchical data structure implementation of the ontology. LCIMs associate the unit product system/processes identified in the first step to foreground parameters and respective background LCI, and
iii. Illustrate the proposed formalism and its usefulness in ensuring consistency of pavement LCA using a cradle-to-gate LCIM implementation for asphalt mixtures.

The schematic workflow to achieve the objective of consistency is illustrated in Figure 2. Consistency can be achieved by digitally representing pavement LCA information using linked data structures. This is followed by mapping the data structures onto background datasets and foreground parameters within the pavement LCA system boundary, to create LCIMs. LCIMs can be used as pavement LCA building blocks. The following section details the ontology based representation of pavement system boundary that serves as the basis for the data structures within LCIMs.

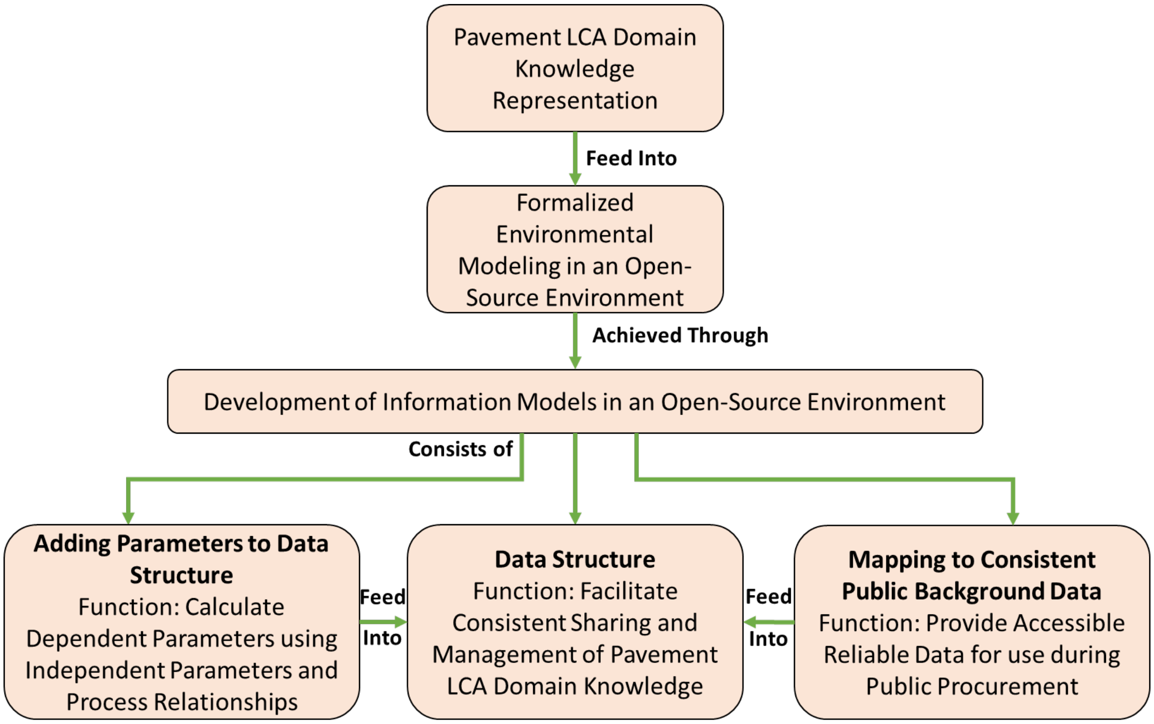


Figure 2. Schematic Workflow to Achieve Consistency

3.1.1 Pavement LCA Domain Knowledge Representation

This section outlines the development of a digital representation of the relationships between flows and processes within the pavement system boundary using the data structure developed in Protégé. As a foundation to consistent pavement LCA data structure, an ontology of the relationships between flows and processes within the pavement system boundary is developed. It lays the foundations for formal digital representation using a set of linked hierarchical data structures. The proposed ontology uses Resource Description Framework (RDF) to represent the unit product system/processes relevant within the pavement LCA system boundary. The building blocks for the ontology for pavement LCA are:

i. *Process Ontology*: A relational grammar using RDF – this is a pavement LCA specific representation of general LCA modeling principles. It adapts the definition of the relationships between LCA flows and processes to the context of pavements.
ii. *Lineage Ontology*: This is a classification of all the pavement LCA specific flows and processes.
iii. *Product System Diagrams*: Using the process ontology and the lineage ontology, the product system diagrams present an exhaustive mapping of all possible flows and processes in the pavement LCA framework. For a given product system and a reference output flow, a set of input flows and output flows are relationally declared. The designation is based on consistency with the pavement LCA framework. Anything inconsistent with the framework is not part of the product

system diagrams and cannot be represented using this ontology. For example, while it will be consistent to include a *crushed stone* as an input flow to both asphalt and concrete product systems, inclusion of *asphalt binder* as an input to a concrete mixture product system would be considered inconsistent.

The rest of this section discusses these building blocks' components in detail.

3.1.1.1 Definition of Process Ontology

Building on the fundamental constructs of process based LCA listed in Fundamental Construct of LCA, this section discusses the relationships between different *flows*, *processes* and *product systems* using the RDF methodology as it applies to pavement LCA. The RDF methods defined for the purpose of relating entities within pavement LCA system boundary are:

i. *IsConsumedBy*: relates a flow object to a process object that it is an input to.
ii. *IsProducedBy*: relates a flow object to a process object that it is an output of.
iii. *IsMovedBy*: relates flow object to a specific transportation process object that is used to move it between locations.

These methods are already implemented in the OpenLCA API (terminology of methods in OpenLCA API is slightly different e.g., "process link" is used to connect two processes and "exchange" is used to connect a flow to a process, however, this difference wouldn't affect the pavement LCA practitioner as they will interact with the interface and not API functionalities). The *IsMovedBy* construct is not a part of the OpenLCA API. It is defined specifically to indicate the role of transportation processes in pavement LCA, allowing for richer representation of semantics. The fundamental relationships between *flows* and *processes* in a general format is illustrated in Figure 3. The flow *F* is an output of *Process 1*, denoted by the method *IsProducedBy* and it is an input to *Process 2*, denoted by *IsConsumedBy*. In between the two *processes,* it is moved by the method *IsMovedBy* by a *transportation process*, that is represented by a product system. The transportation process product system - π (*transportation process*) can, in turn, be comprised of a set of flows and processes describing the outcomes of a specific mode of transportation. For example, if *F* is asphalt binder, *Process 1*, is a process called *Refining of Crude Oil*, *Process 2* is a process called *Production of Asphalt Mixture*, and the *transportation process* involved is *Transportation by Train*, then the RDF triple will represent the life cycle exchange of Asphalt binder *IsProducedBy Refining of Crude Oil*, *IsMovedBy Transportation by Train* and *IsConsumedBy Production of Asphalt Mixture*.

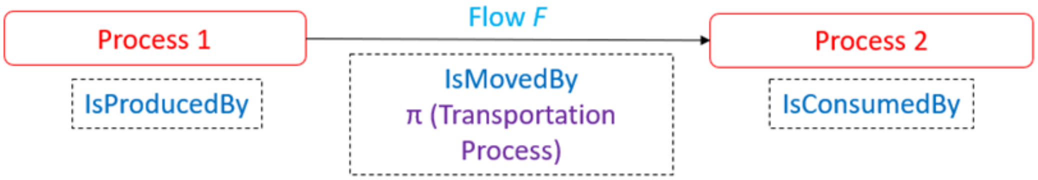


Figure 3. Basic Resource Description Schema for Pavement LCA

A series of these RDF triples connected using a network as expressed in the previous section are used to construct the narrative of the pavement LCA system boundary.

3.1.1.2 Definition of Lineage Ontology

The lineage ontology identifies the different kinds of *flows* and *processes* that lie within the pavement LCA system boundary. Generically from an LCA perspective, all flows can be classified as either *material flows or energy flows* (including both product and intermediate flows) or *waste flows* (representative of entities that are either landfilled or recycled or reused). Further to reflect the context of pavement LCAs, as per the definition of the FHWA framework, the *material*, and *energy* flows are subdivided into materials and energy of interest as shown in the lineage tree in Figure 4. This tree classifies all the different flows in the pavement LCA based on whether they are *materials* or *energy*. Similarly, it also classifies all the *processes* as follows:

1. *Material Extraction and Production Processes*: includes all processes used in the acquisition and processing of pavement materials. These processes belong to the material extraction and production stage of the pavement LCA framework.
2. *Construction Processes*: includes all processes and equipment associated with the construction of initial pavement. These processes belong to the construction stage of the pavement LCA framework.
3. *Transportation Processes*: includes all processes that involve the mobility of materials and energy for other processes. These processes occur at all the life-cycle stages.
4. *Maintenance and Rehabilitation Processes*: includes all processes employed at different times throughout the life of pavement to ensure the serviceability for a specified design or service life. These processes belong to the preservation, maintenance, and rehabilitation stage of the pavement LCA framework.
5. *End-of-Life processes*: includes processes to account for the final disposition and subsequent reuse, processing or recycling of the pavement after it has reached the end of its useful life.

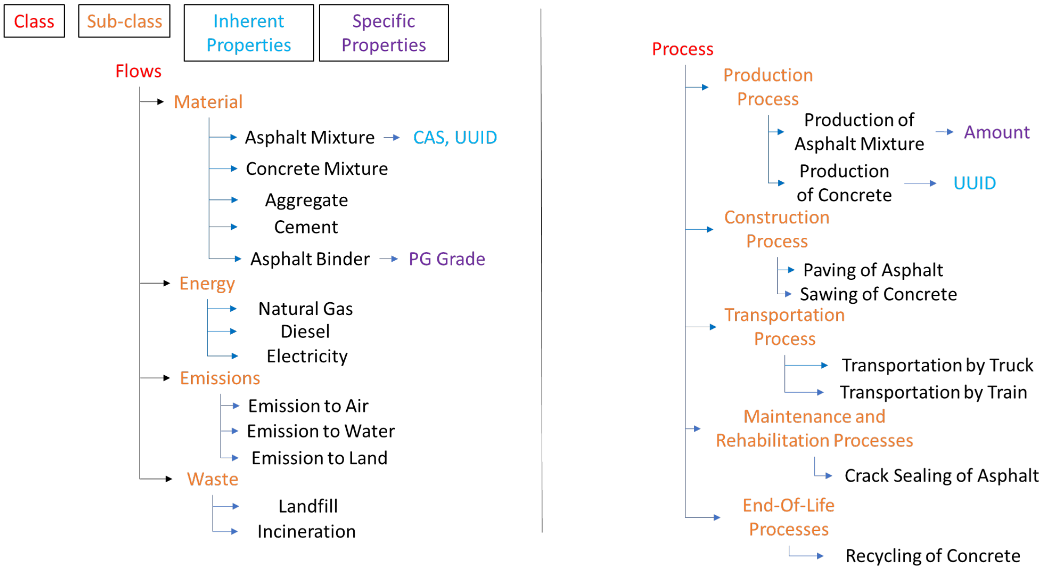


Figure 4. Lineage Ontology

3.1.1.3 Developing Product System Diagrams

The process and lineage ontologies together provide a foundational structure for the *product system diagrams*. These diagrams create an exhaustive mapping of all possible flows and processes in the pavement LCA framework. Figure 5 presents the mapping format using *product system diagrams*. This format illustrates how the different *flows*, *processes* and *product systems* within the system boundary relate to each other, along with the data types necessary to relate them to each other. Hence, each product system diagram is an abstract statement of the possible lists of processes, flows and transportation processes that can be combined in a network to produce the reference product.

The product system mapping ontology developed in this section was translated into a hierarchical data structure in Protégé. The data structure provides a hierarchical system description for entities within pavement LCA. The ontology available in Web Ontology Language (OWL) format in Protégé can be extended to map data models for other aspects of sustainability such as performance or cost in the future. The next section explains the use of the ontological representation to develop LCIMs.

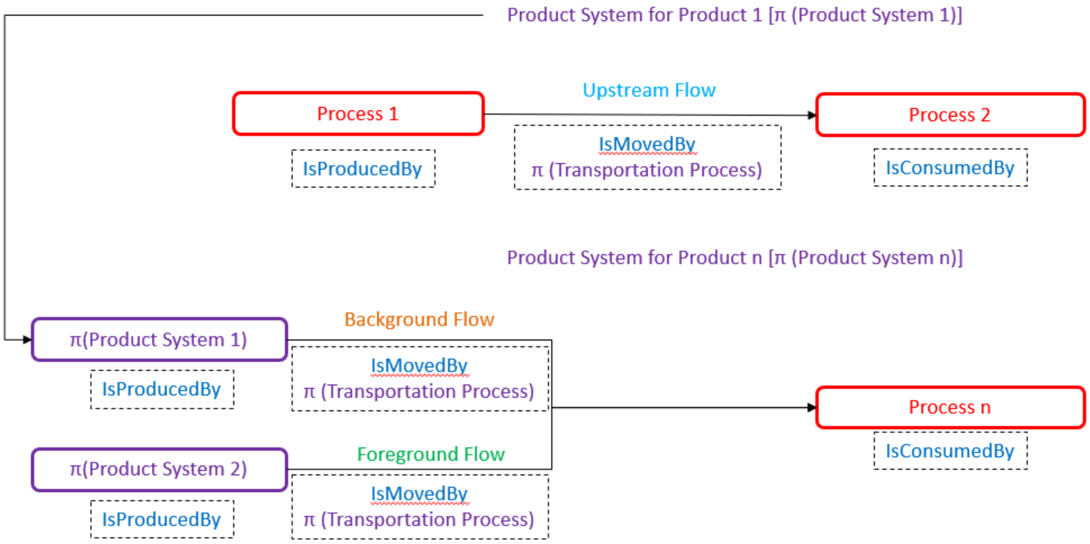


Figure 5. Mapping Format using Product System Diagrams

3.1.2 Development of Baseline Life Cycle Information Models for Pavements

Life Cycle Information Models (LCIMs) are parametric information models developed by mapping the data structures represented using ontology onto background LCI, and foreground parameters that are used in pavement LCA. LCIMs can be used "building blocks" for pavement LCA. This is similar to efforts in defining Industry Foundation Classes (IFC) that form the foundation of Building Information Models (BIM). LCIM implementation will encourage LCA practitioners to spend their efforts in collecting high quality foreground data to populate the parameters, while depending on the modeled structure to ensure consistency of the process relationships and reliability of background LCI. In effect, LCIM will support the development of reusable, modular and standardized LCA models and background datasets thus increasing the consistency of the LCA information and reliability of the EPDs they support. The broader contribution of this methodology is the generalizability of the method used in developing LCIMs – a similar process can be used to ensure consistency of LCA in any domain.

The development of LCIMs is part of a broader collaborative effort. The datasets and process models identified by this research are being used by a collaborative effort at the University of California, Davis for the development of a pavement LCA tool by Applied Pavement Technology to support decision-making. In addition, collaboration with Federal LCA Commons is helping identify publicly available OpenLCA compatible background data flows. The LCA Commons includes representatives from the United States Department of Agriculture (United States Department of Agriculture (USDA), 2019), United States Environmental Protection Agency (United States Environmental Protection Agency (USEPA), 2019), Argonne National Laboratory (Argonne National Laboratory Homepage | Argonne National Laboratory, 2019), National Renewable Energy Laboratory

(National Renewable Energy Laboratory (NREL) Home Page | NREL, 2019), National Energy Technology Laboratory (National Energy Technology Laboratory, 2019), USDA's Forest Product Laboratory (USDA Forest Service - Forest Products Laboratory, 2020), National Institute of Standards and Technology (Metrics and Tools for Sustainable Buildings, 2020), USDOT's FHWA (Sustainable Pavement Program - Sustainability - Pavements - Federal Highway Administration, 2019) and United State Department of Defense (ESOH in Acquisition - DENIX, 2020). The unified goal of LCA commons is to create an open-source collaboration server (LCA Collaboration Server, 2019) that facilitates transparency and reliability in the use of public datasets. In the long term the LCIMs developed in this research effort will support the inclusion of pavement LCA data, in a linked format, in the collaboration server. The following sub-sections describe three elements within the methodology in detail: development of data structures, parameterized models, and mapping to public background data.

3.1.2.1 Development of Data Structures in OpenLCA

The semantics of the digital representation for pavement information models are based in an object-oriented programming approach that reflects the hierarchy defined in the lineage ontology. These pavement information models are developed within the OpenLCA platform. OpenLCA is used for the implementation of this object-oriented hierarchy. The rationale for the selection of OpenLCA is as follows:

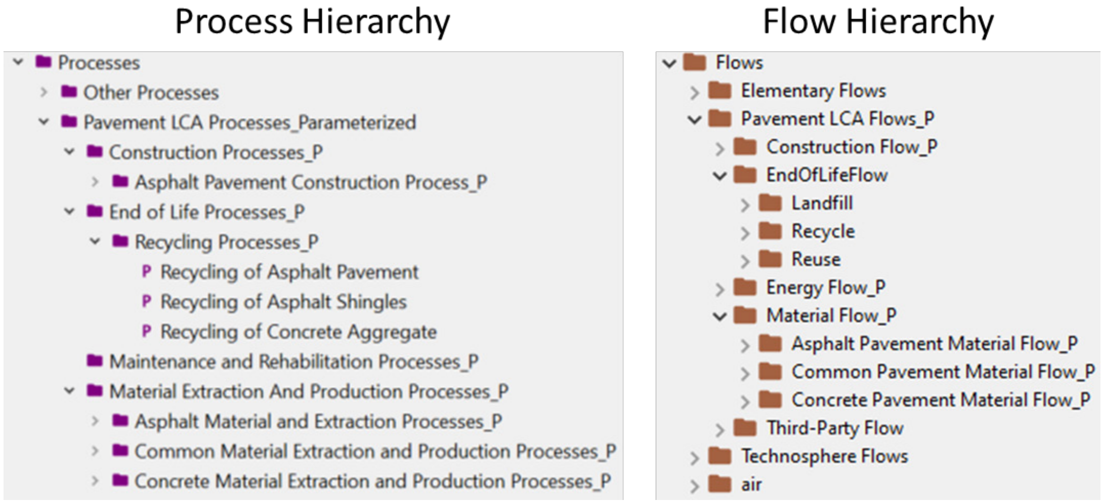
1. The open-source environment affords the properties of transparency and accessibility.
2. The .zolca format also ensures the use of a single platform for integration of background datasets from various other databases and disciplines as they become available.
3. OpenLCA Application Programming Interface (API) already has a set of definitions for the basic entities of LCA such as flows, processes, and products allowing the alignment of pavement domain with the LCA domain.
4. Future pavement LCA specific software can be developed using the OpenLCA API, thus providing domain specific interfaces to LCA software that is powered by OpenLCA.

The *class*[1] definitions for all the *processes* and *flows* in pavement LCA extend the OpenLCA API (GreenDelta/olca-modules, 2020). Each of the specific *material* and *energy*

---

[1] In object-oriented programming, a class is an extensible program-code-template for creating objects, providing initial values for state (member variables) and implementations of behavior (member functions or methods). A sub-class inherits from a class and can have their own properties (e.g., "material" is a sub-class within a class "flow"). Properties are the attributes associated with a class or a sub-class (performance grade associated with a sub-class "asphalt binder"). Parameters are represented as properties while behaviors and relationships can be represented as methods. Sub-classes inherit the properties and methods of parent classes.

flows, and the associated processes defined in the pavement LCA are defined as child classes of the classes defined in the lineage ontology. Hence, a material such as an asphalt mixture is defined by an *AsphaltMixture* class that is a child class of the abstract class *Material* which in turn is a child of the *Flow* class that is inherited from the OpenLCA API. Similarly, all *material* and *energy* flows used in pavement LCA are defined as sub-classes of the abstract classes *Material* and *Energy* which in turn inherit the OpenLCA *Flow* class. For processes, the OpenLCA *Process* class is a parent to the abstract classes for *material extraction and production processes*, *transportation processes*, *construction processes*, *maintenance and rehabilitation processes*, and *end-of-life processes*. A glimpse of process and flow class hierarchies in OpenLCA is illustrated in Figure 6.



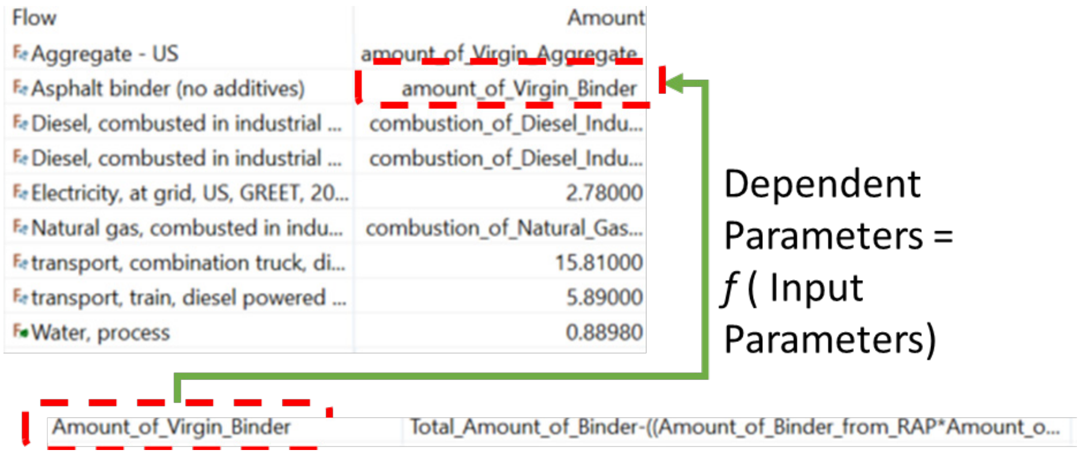
Process Hierarchy

Flow Hierarchy

Figure 6. Hierarchical Data Structure in OpenLCA

3.1.2.2 *Adding Parameters to The Data Structure*

This section explains the identification process for a comprehensive set of parameters to characterize foreground data for pavement LCA, as well as publicly available datasets to define the background datasets. Parameterization refers to representing LCA data using observed process data and process relationships instead of pre-computed numbers in unit process datasets (Cooper, Noon and Kahn, 2012). Parameterization will encourage pavement LCA stakeholders such as material producers, design decision-makers to develop context-specific LCI models by inputting process-specific foreground data to characterize flows that are already mapped to the consistent background data. Hence, an LCA practitioner when using an instance of the asphalt mixture LCA information model will only have to spend their efforts on collecting high quality foreground data to populate the parameters. The information model can then be used as a product system in a pavement LCA. For example, for the case of asphalt mixtures containing Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS), the amount of virgin binder to be used in the mixture will depend on the amount of RAP and RAS as some proportion of binder will be replaced by the asphalt binder already present in RAP and RAS. Hence, if the LCA practitioner inputs the amount of RAP and RAS, the LCIMs will automatically generate the resulting amount of virgin binder in the mixture. This amount of virgin binder will then be reflected as a dependent foreground data value mapped to background product flow "asphalt binder" within the life-cycle information model of asphalt mixture. A glimpse of the pavement information model depicting the parameterization for "asphalt binder" is presented in Figure 7.



Flow	Amount
Aggregate - US	amount_of_Virgin_Aggregate
Asphalt binder (no additives)	amount_of_Virgin_Binder
Diesel, combusted in industrial ...	combustion_of_Diesel_Indu...
Diesel, combusted in industrial ...	combustion_of_Diesel_Indu...
Electricity, at grid, US, GREET, 20...	2.78000
Natural gas, combusted in indu...	combustion_of_Natural_Gas...
transport, combination truck, di...	15.81000
transport, train, diesel powered ...	5.89000
Water, process	0.88980

Amount_of_Virgin_Binder	Total_Amount_of_Binder-((Amount_of_Binder_from_RAP*Amount_o...

Figure 7. Glimpse of Parameterized Information Model

3.1.2.3 Mapping to Consistent Background Data

The association of a background data flow in a life-cycle stage will be a function of the relevance of a technology with respective to the pavement life-cycle stage. For example, from a pavement LCA perspective, a flow for *Diesel, Combusted in Industrial Boiler* represents an energy flow that will be relevant for a *Material Extraction and Production Process* while *Diesel, combusted in Trucks* represents an energy flow that will be relevant to a *Transportation Process*. The collection of background data will require regionalization of the FHWA LCA framework as well. For instance, currently there is only a single product system definition for crude oil extraction in the framework. The use of LCIMs will allow for extension of regionalization as region specific instances of a product system class will reflect where a flow such as crude oil is sourced. Implementation of these classes will result in differences in the LCA outcomes.

Figure 8 presents a high-level detailing of the different background data sets for LCI models for pavements, along with the Federal LCA Commons stakeholders responsible for sharing the datasets. It can be seen from Figure 8 that a data flow may be available from multiple stakeholders, for example, a fossil fuel flow may be available from ANL, NETL or NREL. At present, only the background data available on the LCA collaboration server compatible with OpenLCA are used. A *pavement-specific pedigree approach* is developed (explained in Background Data Quality section) to consistently assess the data quality of these common public background data categories. This approach is based on the updated pedigree matrix developed by USEPA (Edelen and Ingwersen, 2016) and the assessment using this approach will indicate the availability and gaps within the public background data relevant to pavement LCA and reduce the use of proxy data from undocumented diverse sources.

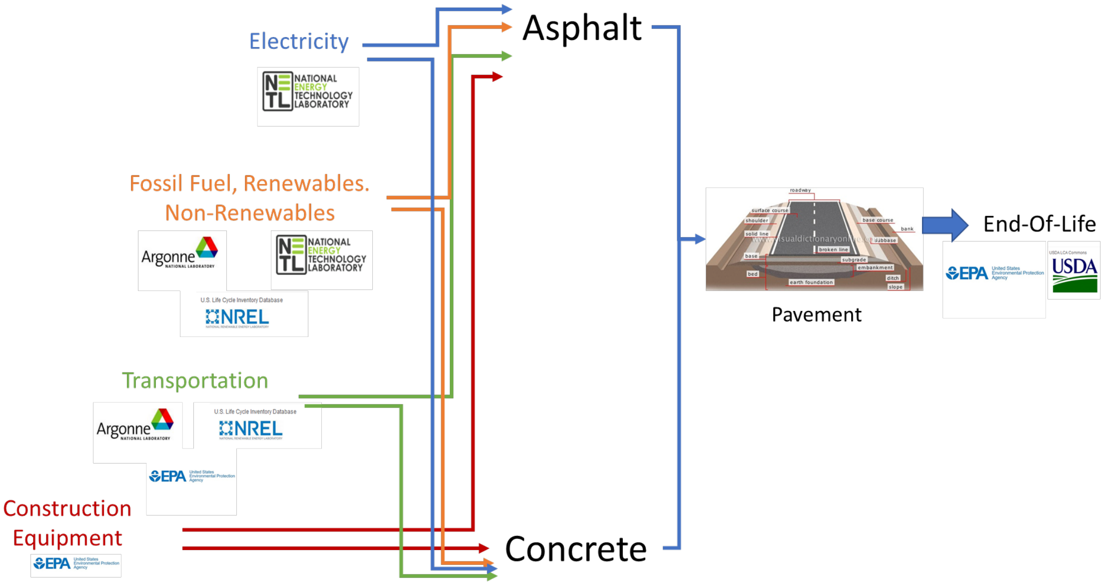


Figure 8. Potential Stakeholders for Background Data Mapping

3.2 Methodology to Achieve Credibility

This section first discusses the computational structure for a deterministic process based LCA followed by discussing an analytical method to propagate parameter uncertainty by Heijungs and Suh, (2002) and finally details on pavement-specific pedigree approach to consistently assess the data quality of both foreground and background data. In a process based LCA, a product system consists of several individual processes and each process consists of product flows and elementary flows. Hence in this matrix-based approach, a process matrix (P) is divided into a technology matrix (A) consisting of product flows (or economic flows) and an intervention matrix (B) consisting of elementary flows (or environmental flows). So, as presented in Figure 9, the first step to model a real world system in the LCA methodology detailed by Heijungs and Suh, (2002) is to compute a square technology matrix, an intervention matrix, and a final demand vector (f). The technology matrix needs to be square for the feasibility of an inverse. An intervention matrix consists of environmental flows from different processes. The final demand vector consists of the reference flow for the product system, for example, 100 short tons of asphalt mixture. Figure 9 presents the computational structure for deterministic process based LCA.

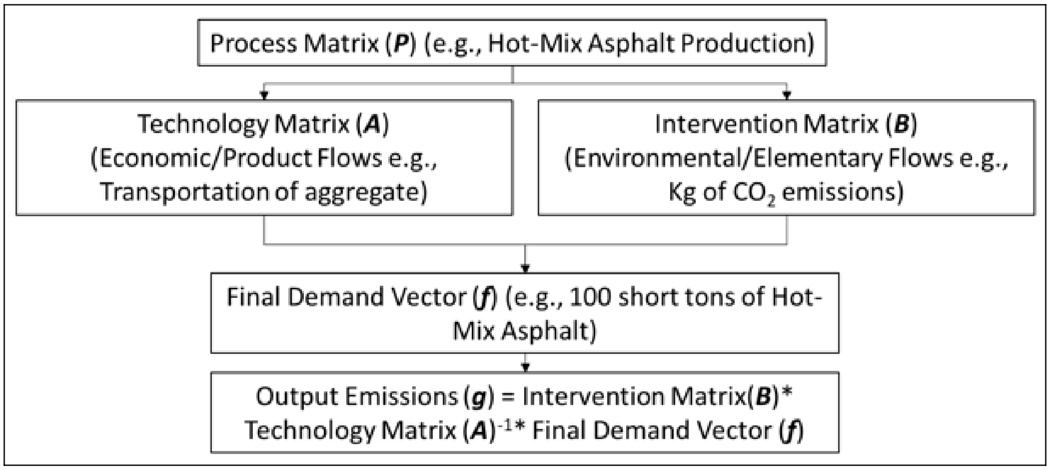


Figure 9. The Computational Structure for Deterministic LCA as per Heijungs and Suh, (2002)

3.2.1 Perturbation of Parameter Uncertainty

Heijungs and Suh (2002) used a perturbation in the input inventory data to represent variability in input data and propagated the variability using Taylor's first order approximation method. Similar to the deterministic LCA methodology presented in Figure 9, the matrices ***A***, ***B*,** and ***f*** are formulated to represent the LCA. Second moments such as the standard deviation, or the Coefficient of Variation (CV) are then multiplied with the deterministic matrices to propagate parameter uncertainty and communicate the variance in output emissions. The results presented in this dissertation use CV for the propagation of uncertainty where CV is the ratio of the standard deviation to the mean (Morgan and Henrion, 2007). The technology matrix and the intervention matrix are both multiplied by the CV to calculate their respective variances. This is presented in Eq.1 and Eq.2.

$$Variance\ in\ \boldsymbol{A} = (CV * \boldsymbol{A})^{2} \qquad \text{–Eq.1}$$

$$Variance\ in\ \boldsymbol{B} = (CV * \boldsymbol{B})^{2} \qquad \text{–Eq.2}$$

All the flows in the technology matrix are multiplied with the scaling vector (***s***) to reflect the actual contributions towards reference flow. The scaling vector (***s***) and another mathematically coined term intensity matrix (***λ***) by Heijungs and Suh, (2002) are used to compute the partial derivatives for both the technology matrix (d***g***/d***A***) and the intervention matrix (d***g***/d***B***). These terms and their role in computing the partial derivatives are presented in Eq.3 to Eq. 6.

$$\boldsymbol{s} = \boldsymbol{A}^{-1} * \boldsymbol{f} \qquad \text{–Eq.3}$$

$$\boldsymbol{\lambda} = \boldsymbol{B} * \boldsymbol{A}^{-1} \qquad \text{--Eq.4}$$

$$d\boldsymbol{g}/d\boldsymbol{A} = -\boldsymbol{\lambda} * \boldsymbol{s} \qquad \text{–Eq.5}$$

$$d\boldsymbol{g}/d\boldsymbol{B} = \boldsymbol{s} \qquad \text{–Eq.6}$$

The partial derivatives signify the change that gets propagated through the LCA. Hence, after the inclusion of parameter uncertainties, the process matrix consists of the variance in the product flows and the elementary flows and is presented in Eq.7

$$\boldsymbol{P} = \begin{bmatrix} d\boldsymbol{g}/d\boldsymbol{A} \\ d\boldsymbol{g}/d\boldsymbol{B} \end{bmatrix} \qquad \text{–Eq.7}$$

The product of the square of the process matrix with the uncertainty incorporated and, the variance in the process matrix provides the variance in $\boldsymbol{g}$ as presented in Eq.8

$$Variance\ in\ \boldsymbol{g} = \sum\ ((\boldsymbol{P}^{\,2}) * Variance\ in\ \boldsymbol{P}) \qquad \text{–Eq.8}$$

The variance in GWP is then determined by multiplying the variance in $\boldsymbol{g}$ with the characterization factors as per the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment report (ipcc.ch, 2014).

$$Variance\ in\ \boldsymbol{GWP} = Characterization\ factors * Variance\ in\ \boldsymbol{g} \qquad \text{–Eq.9}$$

Equivalence interval referring to overlapping ranges of GWP for the competing alternatives when different levels of CV are accounted for is developed to reflect the aleatory uncertainty.

3.2.2 Background Data Quality

The use of LCIMs will shift the focus of the stakeholder to collect reliable foreground data and adapt to consistent background data present within LCIMs. However, it is of primary importance to determine the data quality of these background datasets prior to promoting them as the consistent data to be used within LCIMs. Even though, the expectation for a downstream user would be high quality background data, the limited funding on developing high quality public background datasets constrains this expectation. Hence, this section introduces a pavement-specific pedigree approach to consistently assess the data quality and select background data from various upstream data providers. The *pavement-specific pedigree approach* is based on the USEPA's pedigree matrix (Edelen and Ingwersen 2016) and is aimed to standardize the practice of data quality assessment for the pavement LCA domain.

The pavement-specific pedigree approach is presented in a questionnaire format to ease its application and goes far and beyond the reference USEPA's pedigree matrix to enhance the specificity. The guideline is visionary meaning it is expected to be applied across all pavement LCA projects in the future, however, also includes questions to assess the state of art of background data in the absence of pre-defined data quality objectives. For example, within the criteria "Time Period of Data" question "b" is relevant in the case of individual LCA studies with specific data quality objectives whereas "c" is relevant for assessing the data quality of background data at any given time. In addition, the guideline covers a broad range of topics to assess both foreground and background data with the same level of rigor. For example, within the criteria "Reliability of the data", question "b" and "c" are relevant to assess both the foreground as well as the background data and "d" is relevant for foreground data currently.

Pragmatic desired data qualities are defined (indicated in blue) for each category and limitations to reach this desired data quality are assessed for different background data categories. For example, the desired data quality for the question "Is the inventory checked for mass/energy balance, recalculation etc.?" is the second criteria "Verified data based on a calculation or non-verified data based on measurements – give a score of 2". This means that a background data category with a data quality assessment score of 1 or 2 will meet the desired data quality for question on mass/energy balance and anything above the score of 2 will be identified as a limitation at this time. The long term goal of this assessment is to encourage background data providers to have a data quality assessment score of 1 for all the categories

This pavement-specific pedigree approach is developed as a part of the Federal Highway Administration (FHWA) funded "Roadmap for Background Data" under contract # DTFH6117D00005 awarded to Engineering & Software Consultants, Inc. (ESCINC) and hosted by the Michigan Tech Transportation Institute under a subcontract from ESCINC. The pavement specific pedigree matrix is illustrated for selected public background datasets from the LCA Commons collaboration server in the "Background Data Quality Assessment Results" section. The data quality assessment may be carried out at the flow level and the process level as illustrated below:

3.2.2.1 Flow Level

Flow level assessment enables evaluation of metadata associated with both product flows and elementary flows such as name, unit, CAS number and molecular formula.

3.2.2.1.1 Reliability of the data

Reliability is assessed at the flow level and indicates the methods used to generate the data and verification/validation of these methods. In order to point at the specifics of the data collection methods and their validation, pavement-specific pedigree matrix details four questions within the reliability criterion and the data quality assessment needs to be carried as follows:

- a) Is the inventory data checked for mass/ energy balance, recalculation etc.?
  - i) Verified data based on measurements – give a score of 1
  - ii) Verified data based on a calculation or non-verified data based on measurements – give a score of 2
  - iii) Non-verified data based on a calculation – give a score of 3
  - iv) Documented estimate – give a score of 4

    - v) Undocumented estimate – give a score of 5

- b) What is the status quo for the ownership and continuous support of data?
    - i) Hosts and Owns – give a score of 1
    - ii) Owns but does not host – give a score of 2
    - iii) Hosts but does not owns – give a score of 3
    - iv) Hosts and owns partially – give a score of 4
    - v) Does not host or own – give a score of 5

- c) Is the data regularly updated?
    - i) Regular updates – give a score of 1
    - ii) Less frequent updates – give a score of 2
    - iii) No updates – give a score of 3

- d) Is the data of deterministic nature or are there statistically established confidence intervals stated for the data?
    - i) Confidence Intervals developed considering parameter, scenario and model uncertainty based on directly measured or calculated data – give a score of 1
    - ii) Confidence Intervals developed considering either of parameter, scenario and model uncertainty based on assumed probability distribution – give a score of 2
    - iii) Deterministic value provided – give a score of 3

3.2.2.1.2 Data Collection Methods

Data collection methods are assessed at the flow level and they reflect the robustness of the sampling methods used (i.e. sample size) and the data collection period. In order to point at the specifics of the data collection methods, the pavement-specific pedigree matrix lists two questions within the data collection methods criterion and the data quality assessment needs to be carried as follows:

- a) How representative is the data of the market?
    - i) Representative data from >80% of the relevant market, over an adequate period – give a score of 1
    - ii) Representative data from 60-79% of the relevant market, over an adequate period OR representative data from >80% of the relevant market, over a shorter period – give a score of 2
    - iii) Representative data from 40-59% of the relevant market, over an adequate period OR representative data from 60-79% of the relevant market, over a shorter period – give a score of 3

    - iv) Representative data from <40% of the relevant market, over an adequate period OR representative data from 40-59% of the relevant market, over a shorter period – give a score of 4
    - v) Unknown OR data from a small number of sites and from shorter periods – give a score of 5

- b) How compatible is the life-cycle inventory data with TRACI 2.1 impact assessment method from LCA Commons?
    - i) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 1
    - ii) Life-cycle inventory data is enough to calculate only 6 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 2
    - iii) Life-cycle inventory data is enough to calculate only 3 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 3
    - iv) Life-cycle inventory data is not compatible with TRACI 2.1 impact assessment method from LCA Commons – give a score of 4

3.2.2.1.3 Time Period of Data

Time period is assessed at the flow level and is used for either assessing the age difference between the temporal DQG and the age of the data or just the actual age of the data. In order to point the specifics of time period, the pavement-specific pedigree matrix lists three questions within the time period criterion and the data quality assessment needs to be carried as follows:

- a) Does the data capture seasonal variations?
    - i. All three (fall, spring and summer) seasons are covered – give a score of 1
    - ii. Only two out of three seasons are covered – give a score of 2
    - iii. Only one season is covered – give a score of 3
    - iv. Not Specified – give a score of 4

- b) How well is the time period the data correlated with the data quality objective?
    - i. Less than 3 years of difference – give a score of 1
    - ii. Less than 6 years of difference – give a score of 2
    - iii. Less than 10 years of difference – give a score of 3
    - iv. Less than 15 years of difference – give a score of 4
    - v. Age of data unknown or more than 15 years – give a score of 5

- c) How old is the data at the time of data quality assessment?
    - i. Less than 3 years old – give a score of 1

    - ii. Less than 6 years old – give a score of 2
    - iii. Less than 10 years old – give a score of 3
    - iv. Less than 12 years old – give a score of 4
    - v. Age of data unknown or more than 15 years – give a score of 5

Now, the question “b” is relevant in the case of individual LCA studies with specific data quality objectives whereas “c” is relevant for assessing the data quality of background data without specific data quality objective. As the scope of this roadmap is relevant to background data only, questions “a” and “c” are used to assess the data quality.

3.2.2.1.4 Geography of Data

Geography is assessed at the flow level and is designed to capture differences in data quality related to differences in area of study and resolution between the geography DQGs and the data used for modeling. In order to point the specifics of time period, the pavement-specific pedigree matrix lists two questions within the geography criterion and the data quality assessment needs to be carried as follows:

- a) How well is the geography of the data correlated with the data quality objective?
    - i. Data from same resolution AND same area of study – give a score of 1
    - ii. Within one level of resolution AND a related area of study – give a score of 2
    - iii. Within two levels of resolution AND a related area of study – give a score of 3
    - iv. Outside of two levels of resolution BUT a related area of study – give a score of 4
    - v. From a different or unknown area of study – give a score of 5
- b) What is the regional granularity associated with the data?
    - i. State level – give a score of 1
    - ii. Country level – give a score of 2
    - iii. Continental level – give a score of 3
    - iv. Global level – give a score of 4
    - v. Data granularity unknown – give a score of 5

Now, the question “a” is relevant in the case of individual LCA studies with specific data quality objectives whereas “b” is relevant for assessing the data quality of background data without specific data quality objective. As the scope of this roadmap is relevant to background data only, question “b” is used to assess the data quality.

3.2.2.1.5 Technology of Data

Technology is assessed at the flow level and is designed to capture process design, operating conditions, material quality, and process scale. In order to point the specifics of technology, the pavement-specific pedigree matrix lists two questions within the technology criterion and the data quality assessment needs to be carried as follows:

a) How well is the technology of the data correlated with the data quality objective?
    i. All technology categories are equivalent – give a score of 1
    ii. Three of the technology categories are equivalent – give a score of 2
    iii. Two of the technology categories are equivalent – give a score of 3
    iv. One of the technology categories are equivalent – give a score of 4
    v. None of the technology categories are equivalent – give a score of 5

b) How well is the technology of the data described?
    i. Specified – give a score of 1
    ii. Not Specified – give a score of 2

Now, the question "a" is relevant in the case of individual LCA studies with specific data quality objectives whereas "b" is relevant for assessing the data quality of background data without specific data quality objective. As the scope of this roadmap is relevant to background data only, question "b" is used to assess the data quality.

3.2.2.2 Process Level

Process level review enables the assessment of level of detail pertaining to a unit process i.e. whether it is possible to obtain specific unit process information or only aggregated process (combined processes to maintain confidentiality) information is available.

3.2.2.2.1 Process Review

Process review is assessed at the process level and is designed to evaluate the level of review a dataset has undergone at the unit process level. In order to point the specifics of process review, the pavement-specific pedigree matrix lists one question within the process review criterion and the data quality assessment needs to be carried as follows:

a) How well is the process reviewed?
    i. The process has documented reviews by a minimum of two types of third-party reviewers – give a score of 1
    ii. The process has documented reviews by a minimum of two types of reviewers, with one being a third party – give a score of 2
    iii. The process has documented review by a third-party reviewer – give a score of 3
    iv. The process has documented review by an internal reviewer – give a score of 4
    v. The process has no documented review – give a score of 5

3.2.2.2.2 Process Completeness

Process completeness is assessed at the process level and is designed to evaluate the level of review a dataset has undergone at the unit process level. In order to point the specifics of process review, the pavement-specific pedigree matrix lists one question within the process review criterion and the data quality assessment needs to be carried as follows:

a) How complete is the process?
    i. >80% of determined flows within the process have been evaluated and given a value – give a score of 1
    ii. 60-79% of determined flows within the process have been evaluated and given a value – give a score of 2
    iii. 40-59% of determined flows within the process have been evaluated and given a value – give a score of 3
    iv. <40% of determined flows within the process have been evaluated and given a value – give a score of 4
    v. Process completeness not scored – give a score of 5

The results of the data quality assessment for common background data categories found within pavement LCA are detailed in

4 Chapter 4: Results

This chapter illustrates the following by considering an example of Hot-Mix Asphalt (HMA) mixtures containing varying amounts of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS):

1. Aleatory uncertainty: The aleatory uncertainty is illustrated using both the OpenLCA technology agnostic approach discussed by Heijungs and Suh, (2002) and furthered by Groen and Heijungs, (2016) as well as by running Monte Carlo Simulations using Life Cycle Information Models (LCIMs) developed in OpenLCA. The purpose of this illustration was to determine whether the margins of error in potential environmental impacts are an artifact of the selected methodology or the underlying data itself. for propagating parameter uncertainty. Specifically, the input variations in electricity and natural gas are propagated to determine the equivalence range for GWP of alternative HMA mixtures.
2. Epistemic uncertainty: The epistemic uncertainty is illustrated by assessing the sensitivity of GWP to background data for electricity and asphalt binder. This assessment is conducted using LCIMs developed in OpenLCA.
3. Protocol uncertainty: The epistemic uncertainty is illustrated by assessing the sensitivity of GWP to the economic allocation coefficients for crude oil refining co-products at a Petroleum Administrative Defense District (PADD) region granularity obtained using Yang, (2014). This assessment is conducted using LCIMs developed in OpenLCA.

The following sections discuss each of these in detail.

4.1 Aleatory Uncertainty

The parameter uncertainty due to diurnal variations in energy consumption is the metric used for aleatory uncertainty in this dissertation. The analytical approach will involve the computation of LCA through manual construction of matrices while the Monte Carlo Simulations can be conducted by specifying the uncertainty value for foreground parameters within LCIMs. The aleatory uncertainty is propagated through four alternative design mixtures that are as follows:

1. Virgin asphalt mixture
2. Asphalt mixture with 20% RAP
3. Asphalt mixture with 35% RAP
4. Asphalt mixture with 15% RAP and 3% RAS

The LCIMs are formed by combining the design data for the above four mixtures along with the background LCI data used in Mukherjee, (2016). LCA for asphalt mixtures by Mukherjee, (2016) is an ISO Standard 14040 compliant LCA that is in keeping with the FHWA framework by Harvey et al., (2016) and serves as the supporting LCA for the Product Category Rule (PCR) for the Environmental Declaration (EPD) program hosted by the National Asphalt Pavement Association (NAPA). It uses a declared unit of 1 U.S short ton of asphalt mixture and the system boundary is from cradle to gate, with the gate being defined as the point at which the asphalt mixture is transferred from the silo at an asphalt plant (i.e. by using the life-cycle stages A1, A2 and A3 specified in EN 15804:2012). Foreground data for Mukherjee, (2016) was collected from 40 asphalt plants across North America and the NREL U.S. LCI database was used for background data. Mukherjee, (2016) quantified the potential environmental impacts for a limited number of plants. This dissertation furthers this analysis by quantifying the potential impacts at different Petroleum Administrative Defense District (PADD) region granularity. The asphalt plant data from Mukherjee, (2016) is grouped at the PADD region granularity i.e. mean, standard deviation for foreground data of energy, electricity are calculated at PADD region granularity. The United States has been divided into five PADD regions as shown in Figure 11 to assess the Environmental Impact Assessment's (EIA's) regional petroleum product supplies.

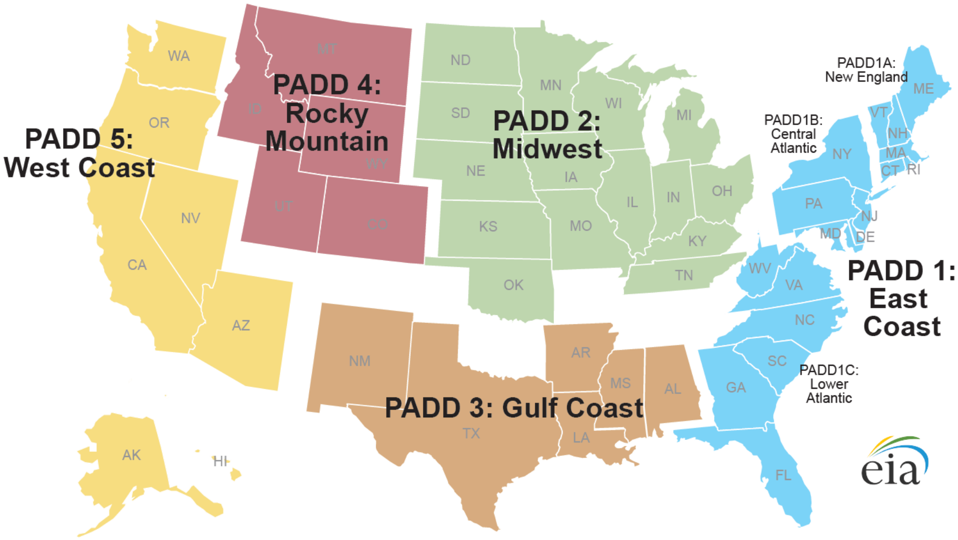


Figure 10. PADD Region Division (Source: EIA)

The consideration of PADD region granularity for the purpose of this dissertation is also influenced by the fact that the source of crude oil differs for different PADD regions and hence, the background data flow for asphalt binder will also be different. At this time, this level of granularity is not available for asphalt binder flow, however, in future, the LCIMs can facilitate the inclusion of asphalt binder production at the PADD region granularity.

The aleatory uncertainty is propagated using both the analytical approach developed by Heijungs and Suh, (2002) in a technology agnostic manner and through Monte Carlo Simulation in OpenLCA. A normal distribution is assumed for propagating the uncertainty using Monte Carlo Simulation and the corresponding mean and standard deviations are calculated. For propagating the uncertainty using the method detailed by Heijungs and Suh, (2002), a square technology matrix is developed through different methods specified by Heijungs and Suh, (2002) e.g., adding hollow processes through zeroes in case of insufficient upstream data. The employment of methods mentioned in Heijungs and Suh, (2002) is data-specific and needs to be decided by the LCA practitioner based on the upstream data available for an LCA study. Output product flows in a process are assigned a positive value and input product flows in a process are assigned a negative value while forming the technology matrix. Table 1 presents the product flows required to produce virgin asphalt mixtures (foreground data) based on Mukherjee, (2016). The other three mixtures contain additional product flows for RAP and RAS.

Table 1. Product Flows

Aggregate-US
Bitumen, in refinery-US
Diesel combusted in industrial boiler-US
Diesel combusted in industrial equipment-US
Electricity, at the grid, US GREET 2012-US
Natural Gas combusted in industrial boiler-US
Transport, combination truck, diesel powered-US
Transport, train, diesel powered, US

These foreground product flows are produced from background processes and the technology matrix consists of all these processes. However, in the absence of background data for processes, methods such as hollow processes mentioned in the above paragraph are used to formulate a square technology matrix. This constituted a 31*31 technology matrix for a conventional asphalt mixture with 0% RAP and 32*32 matrices for mixtures containing 20% RAP and 35% RAP and 33*33 matrices for mixtures containing 15% RAP and 3% RAS. The intervention matrix consisted of kg of carbon-di-oxide (CO_2) equivalent obtained by characterizing and summing CO_2, methane (CH_4), and nitrous oxides (NO_2) emitted. The final demand vector consisted of units of asphalt mixture produced i.e., one short ton of asphalt mixture is considered as the reference flow that is same as the declared unit defined in Mukherjee, (2016) and zeroes in all other places.

The deterministic LCA outcomes for the four alternative asphalt mixtures calculated at the data granularity of PADD regions is presented in Table 2. The results of the deterministic LCA based on the methodology described in Figure 9 showed that GWP decreases with the increase in the amount of virgin binder replaced and this is in accordance with the previous literature.

Table 2. Deterministic LCA Outcomes

Asphalt Mixture	GWP (Kg of CO2 eq.)

	PADD1	PADD2	PADD3	PADD4	PADD5
Virgin Mixture	44.37	42.80	53.52	40.78	44.68
Mixture with 15% RAP and 3% RAS	42.58	41.00	51.73	38.99	42.89
Mixture with 20% RAP	42.34	40.78	51.50	38.76	42.66
Mixture with 35% RAP	40.79	39.23	49.95	37.21	41.11

The next step is to explore the extent of the reduction of GWP and assess its sensitivity to aleatory uncertainties within product flows such as electricity and energy. Natural gas is found to be the most significant contributor to GWP among energy supplies and hence is the parameter considered for energy. The variance is determined by multiplying the point estimates for these input product flows with CV.

The research presented in the dissertation used a square matrix for CV as opposed to a single value for CV as mentioned in Groen and Heijungs, (2016), to facilitate the incorporation of uncertainty for each individual foreground product flows. The amounts of aggregate, RAP or asphalt binder in a given asphalt mixture are specific to the mix-design being used and their values are deterministic by design. However, natural gas and electricity flows vary from plant to plant. As per Mukherjee, (2016) the value for electricity and natural gas flows vary based on the geographical location of an asphalt plant and can be sensitive to diurnal variations in temperature and humidity. Data collected from 40 asphalt plants across North America were grouped as per PADD region granularity and data is analyzed to establish 95% confidence intervals for these specific input parameters. This research first evaluates the variance in ***g*** (kg of GHG emissions) by multiplying the point estimates for both natural gas and electricity flows with CV as explained in the Methodology section (Eq.1 to Eq.8) and later characterizes them as variance in GWP.

The results of aleatory uncertainty analysis are presented as equivalence intervals that can support LCA decision-making during material procurement. In the context of this dissertation, equivalence intervals are defined as the range within which the environmental impact from different alternatives may be considered the same due to inherent uncertainty within the data. When the difference between two competing LCA outcomes falls within the interval, the difference can be attributed possibly to input aleatory uncertainty rather than any substantial difference in environmental impact. As in this analysis, the underlying aleatory uncertainty may be resulting from diurnal variations in weather as well as due to geographical and climate-related variation. Specifically, for the purpose of illustration, the equivalence interval refers to the range of GWP for which the savings in the GWP because of higher RAP, RAS use may be discounted due to the variation in electricity and energy consumption. Mathematically, the equivalence interval refers to overlapping ranges of GWP for the different options when different levels of CV are accounted for. Hence, all the values of GWP within the equivalence interval for a CV in electricity or natural gas can be treated as equivalent for decision-making purposes during material procurement. The equivalence intervals calculated using both analytical approach by Heijungs and Suh, (2002) and Monte Carlo Simulations at PADD region granularity for alternative asphalt mixtures is presented in Figure 12 through Figure 31. The respective CV and interpretation of equivalence intervals are presented with each figure.

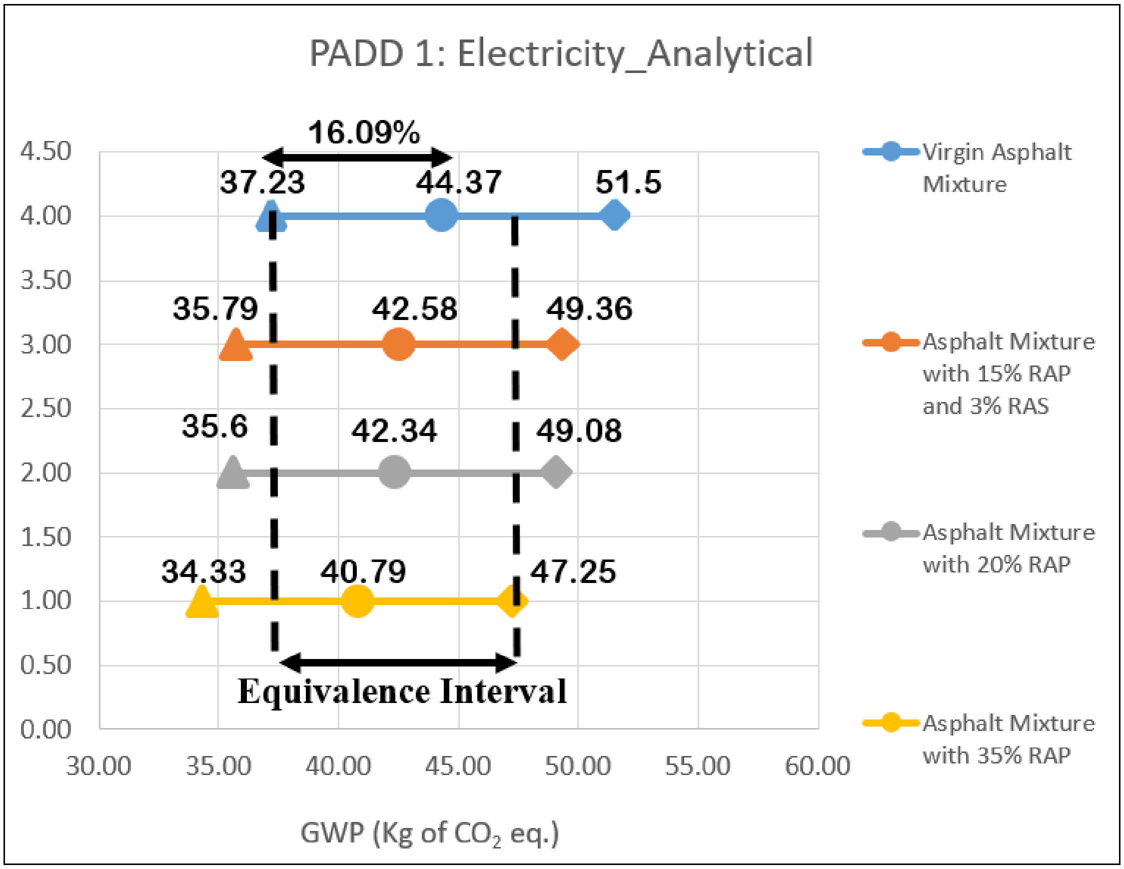


Figure 11. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 1 Foreground Uncertainty in Electricity by Analytical Method

△ ***CV=-0.35*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.35***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.35 and +0.35 (based on the mean and SD calculated for plants in PADD1 region) in electricity is presented in Figure 11. The equivalence interval is from 37.23 kg of CO_2 eq. to 47.25 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 16.09% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

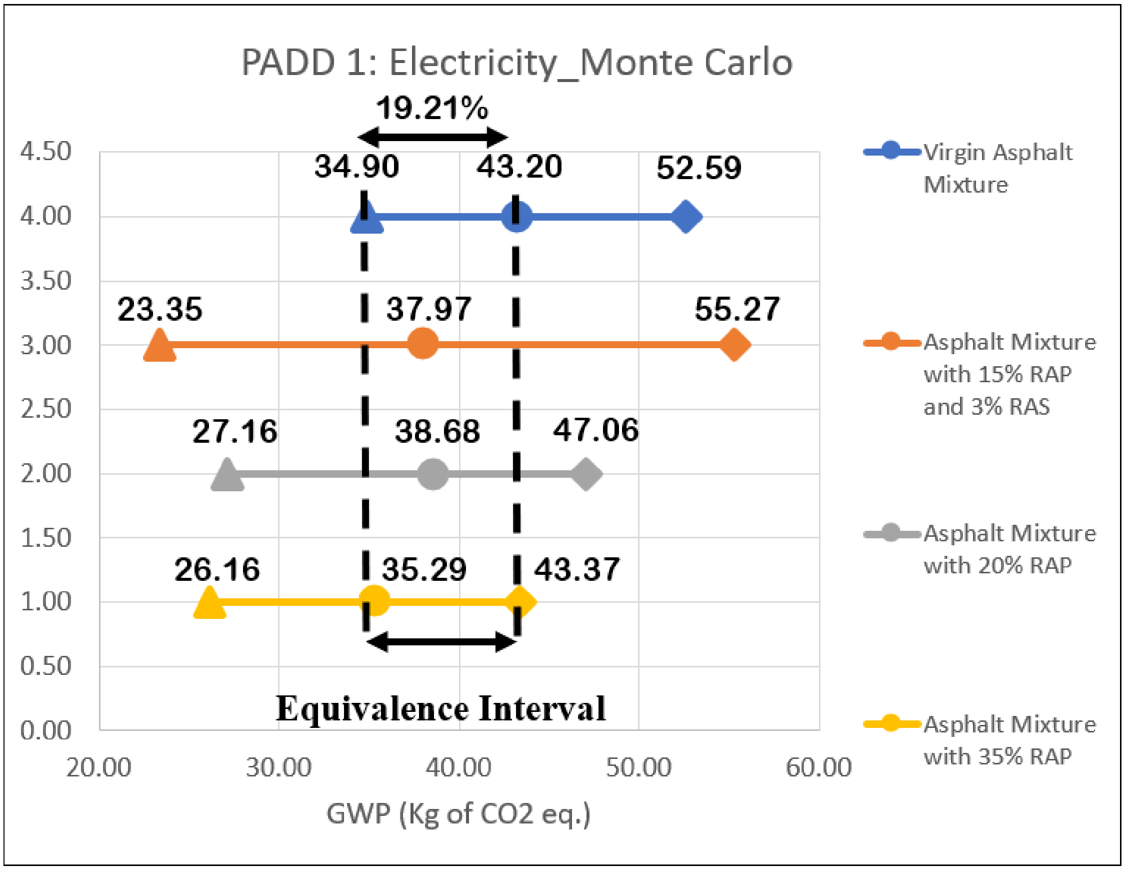


Figure 12. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 1 Foreground Uncertainty in Electricity by Monte Carlo Method

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD1 region is presented in Figure 12. The equivalence interval is from 34.90 kg of CO_2 eq. to 43.37 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 19.21% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

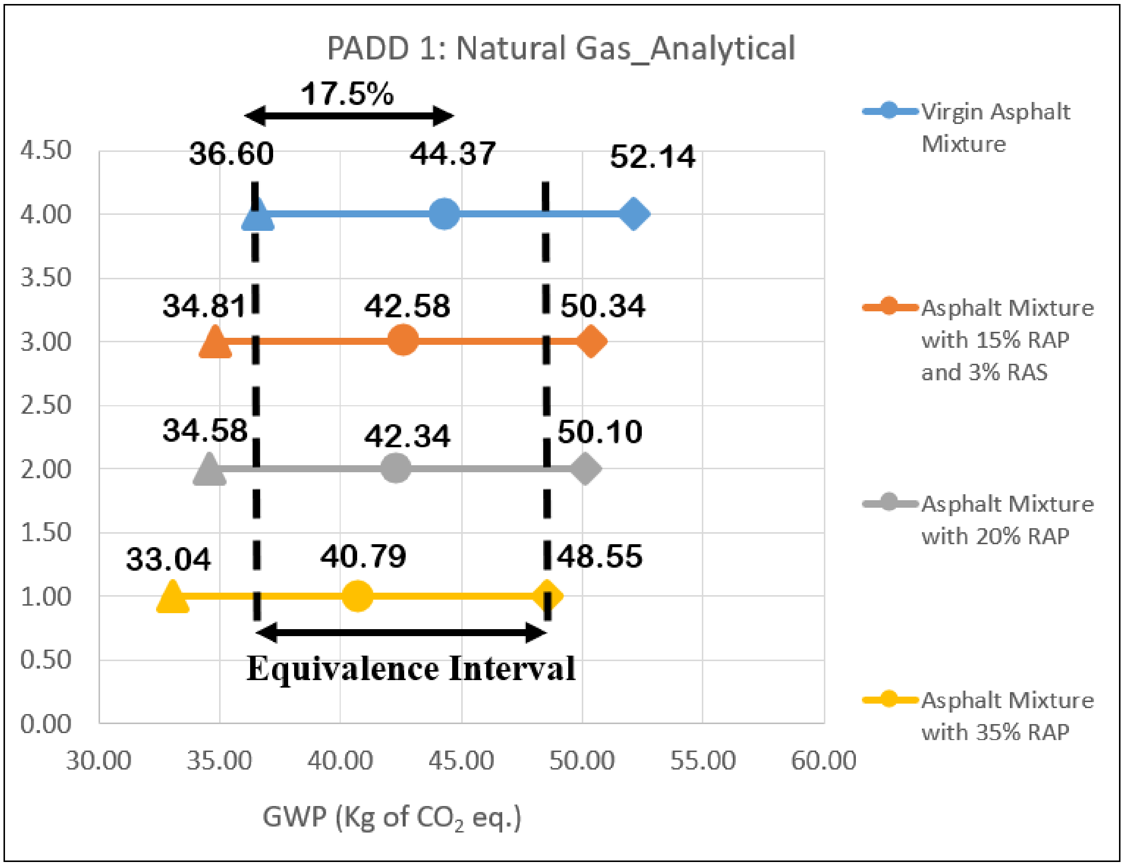


Figure 13. Sensitivity of GWP (Kg of CO_2 eq) to PADD 1 Foreground Uncertainty in Natural Gas by Analytical Method

△ ***CV=-0.3*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.3***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.3 and +0.3 (based on the mean and SD calculated for plants in PADD1 region) in natural gas is presented in Figure 13. The equivalence interval is from 36.60 kg of CO_2 eq. to 48.55 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 17.5% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

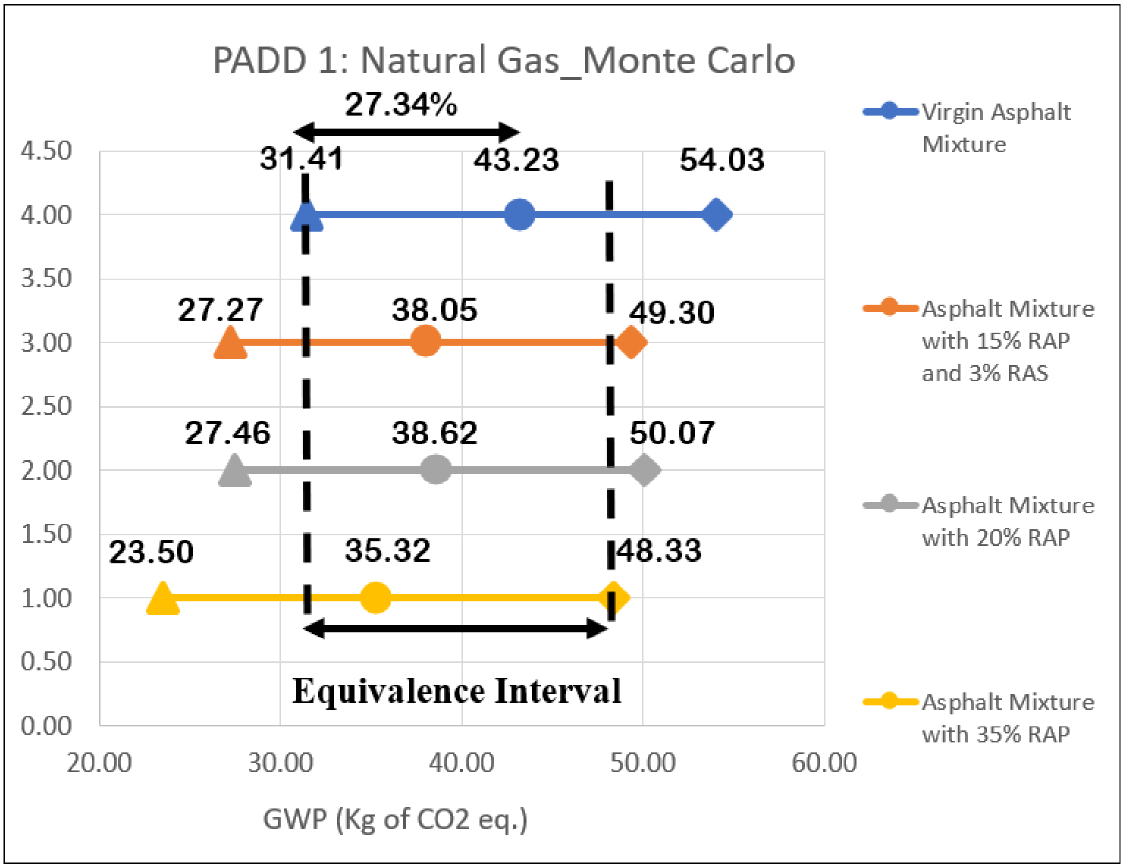


Figure 14. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 1 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of natural gas data in PADD1 region is presented in Figure 14. The equivalence interval is from 31.41 kg of CO_2 eq. to 48.33 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 27.34% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

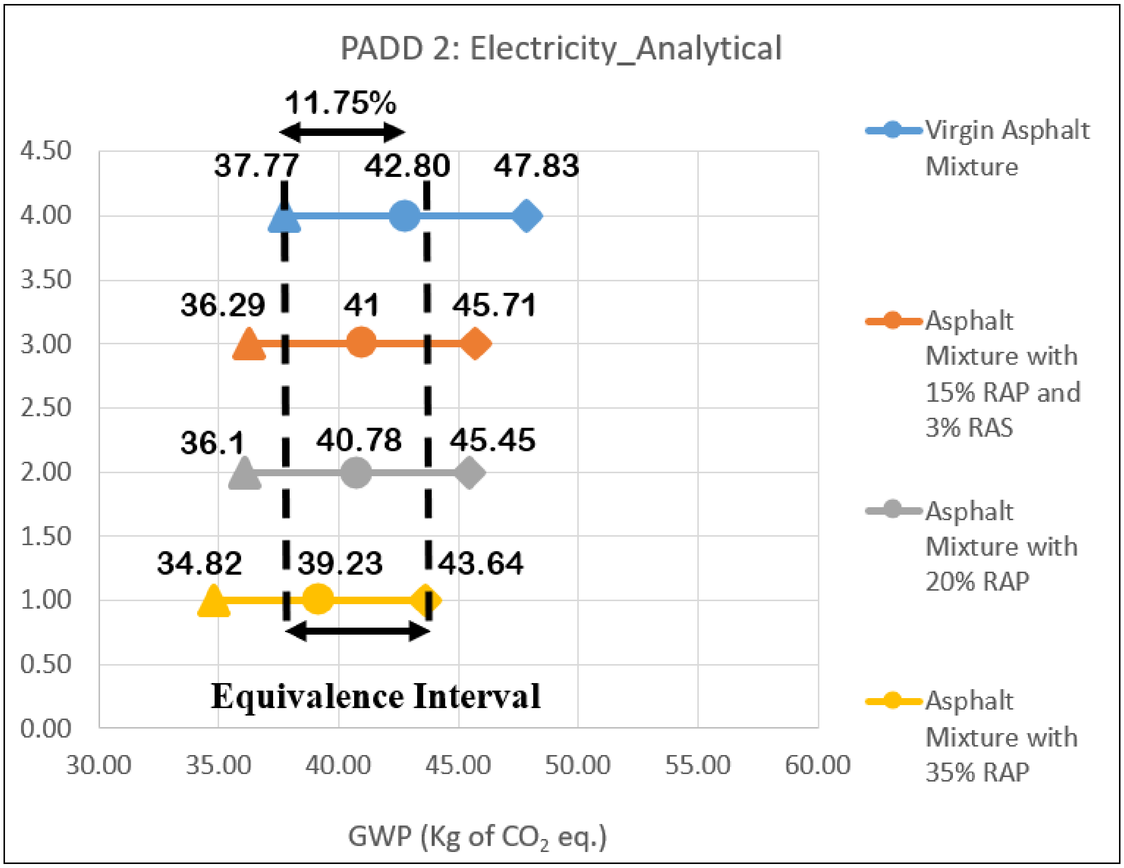


Figure 15. Sensitivity of GWP (Kg of CO_2 eq) to PADD 2 Foreground Uncertainty in Electricity by Analytical Method

△ ***CV=-0.3*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.3***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.3 and +0.3 (based on the mean and SD calculated for plants in PADD2 region) in electricity is presented in Figure 15. The equivalence interval is from 37.77 kg of CO_2 eq. to 43.64 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 11.75% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

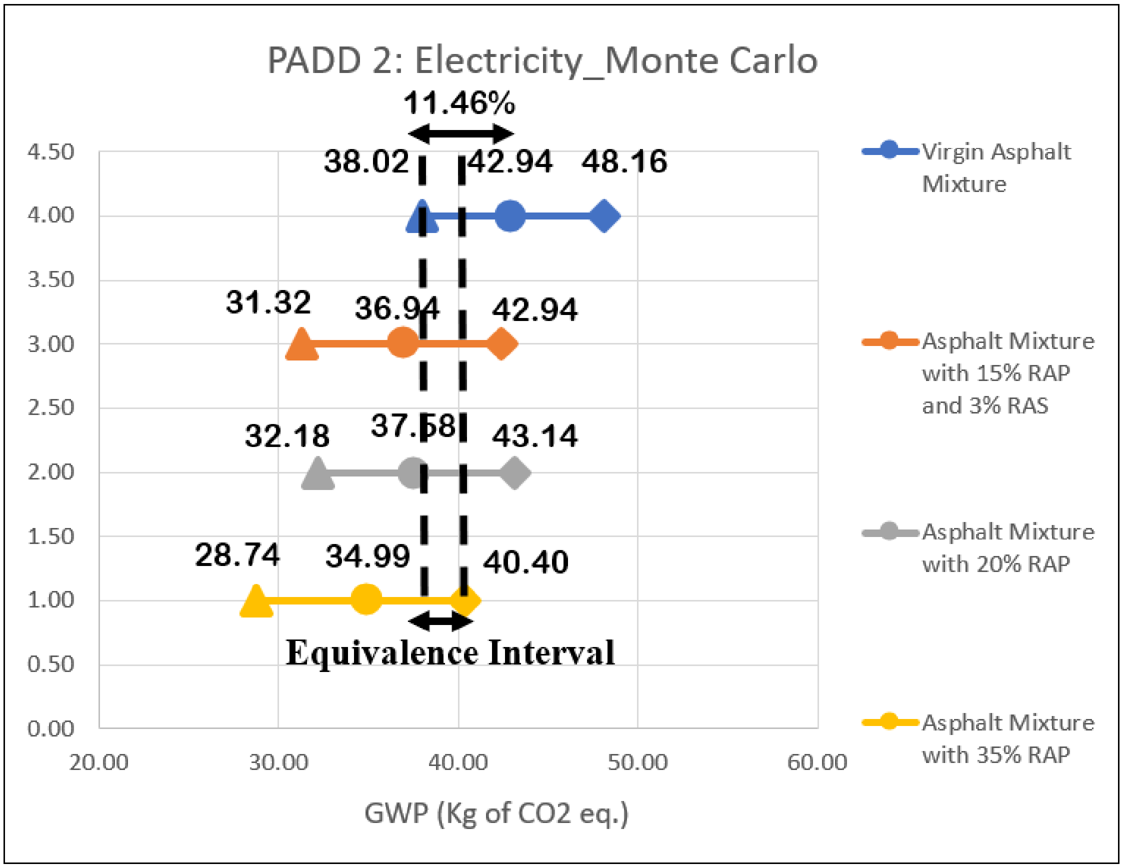


Figure 16. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 2 Foreground Uncertainty in Electricity by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD2 region is presented in Figure 16. The equivalence interval is from 38.02 kg of CO_2 eq. to 40.40 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 11.46% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

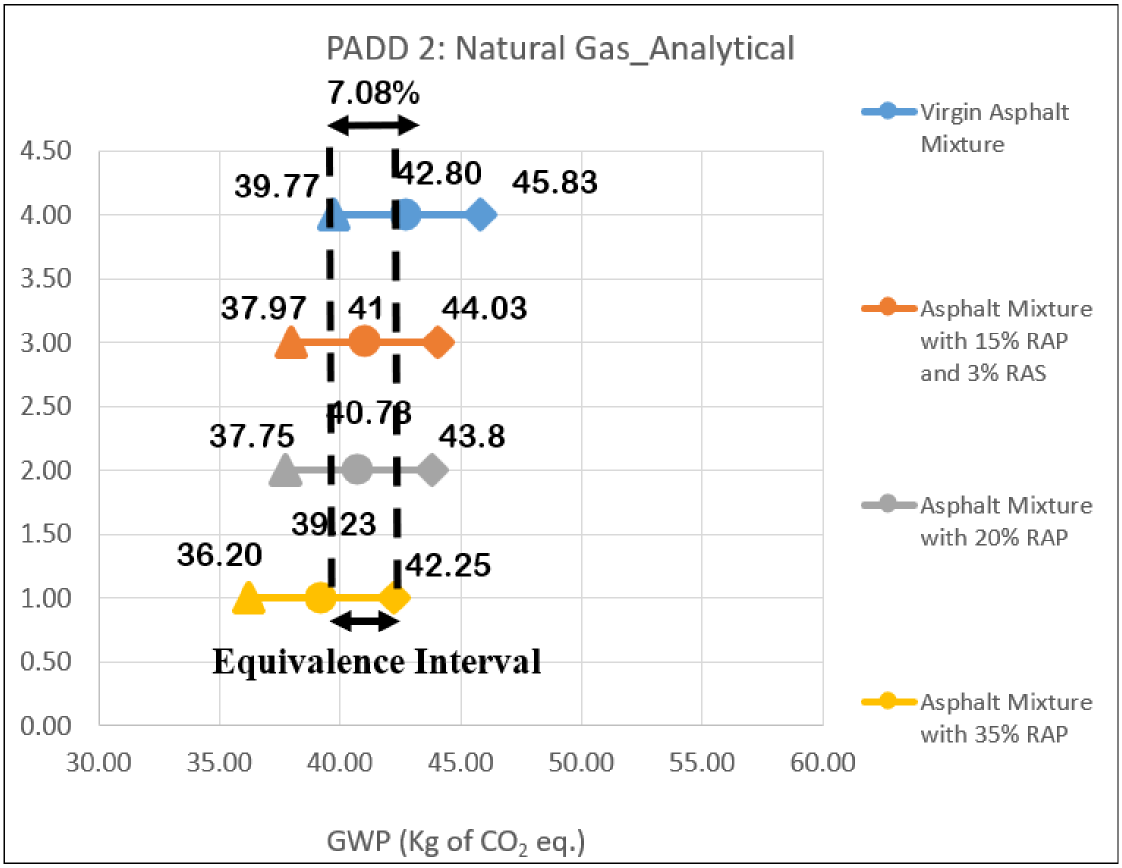


Figure 17. Sensitivity of GWP (Kg of CO_2 eq) to PADD 2 Foreground Uncertainty in Natural Gas by Analytical Method

△ ***CV=-0.12*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.12***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.12 and +0.12 (based on the mean and SD calculated for plants in PADD2 region) in natural gas is presented in Figure 17. The equivalence interval is from 39.77 kg of CO_2 eq. to 42.25 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15%% RAP and 3% RAS need to be at least 7.08% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

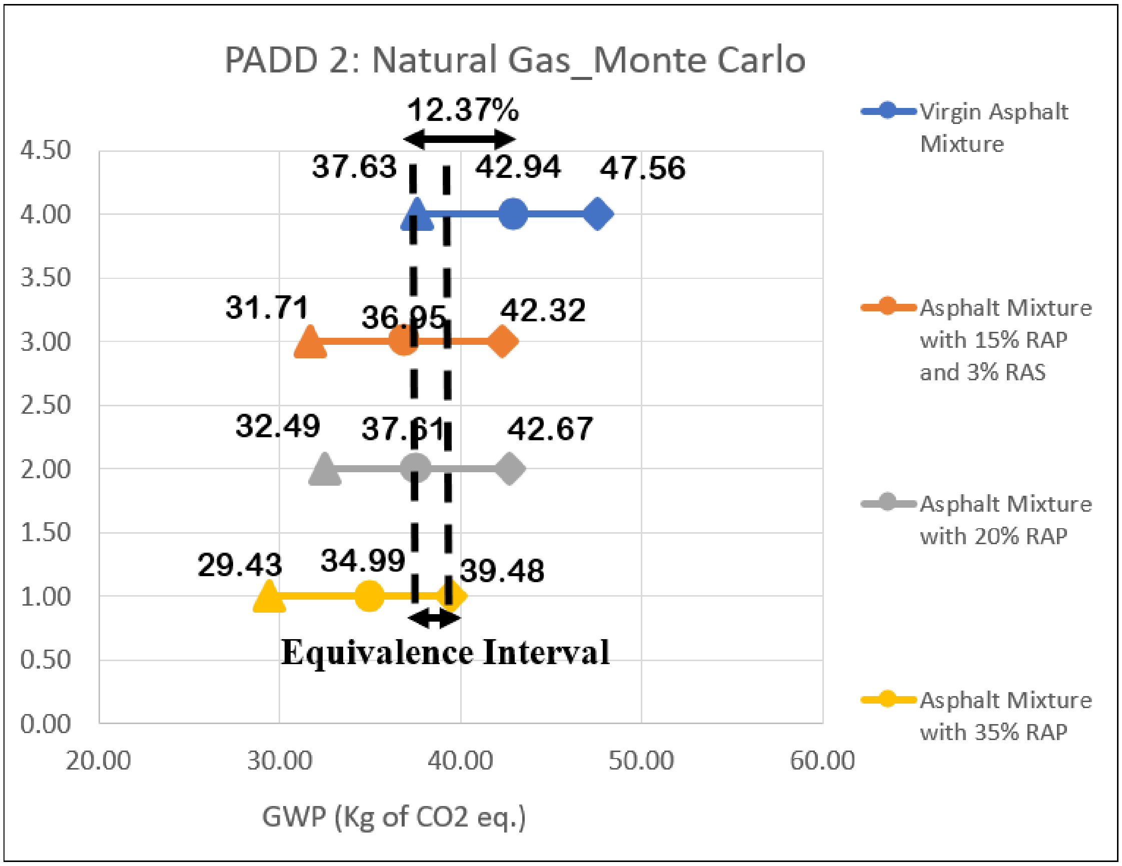


Figure 18. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 2 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD2 region is presented in Figure 18. The equivalence interval is from 37.63 kg of CO_2 eq. to 39.48 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 12.37% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

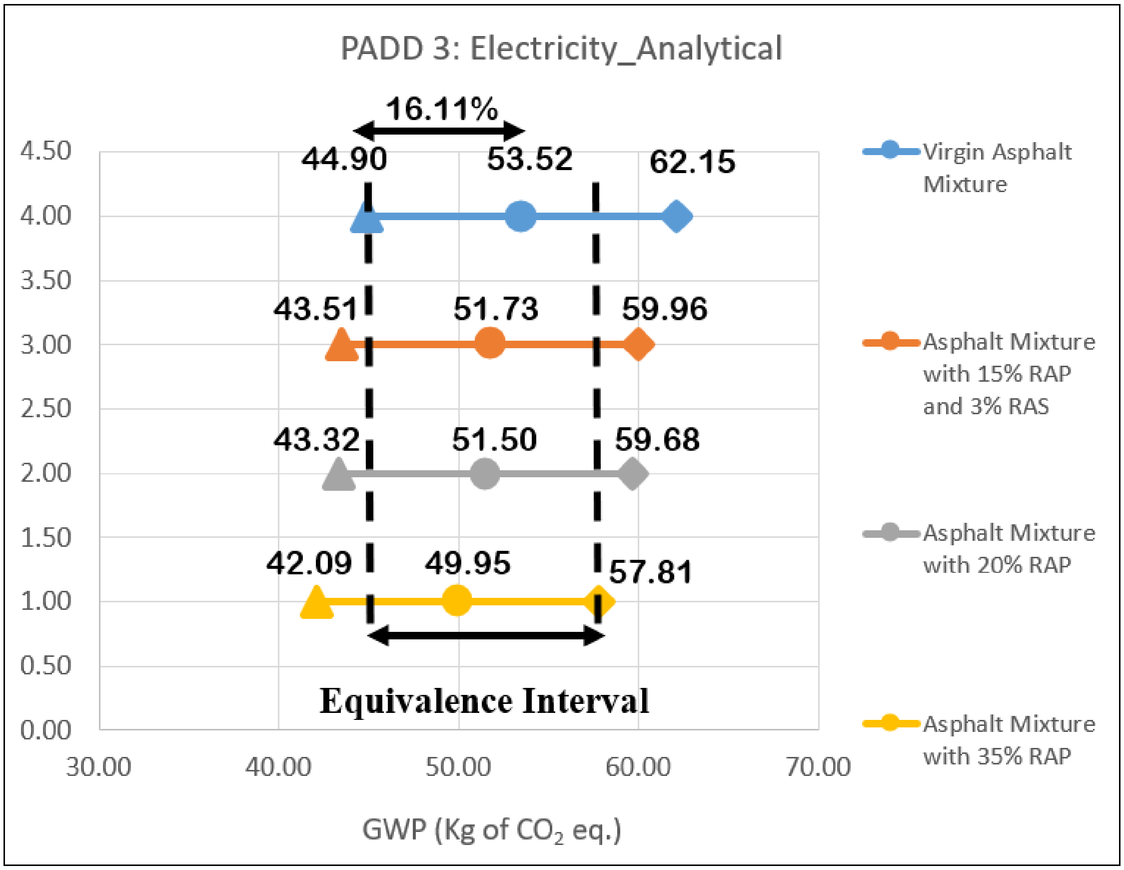


Figure 19. Sensitivity of GWP (Kg of CO_2 eq) to PADD 3 Foreground Uncertainty in Electricity by Analytical Method

△ ***CV=-0.4*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.4***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.4 and +0.4 (based on the mean and SD calculated for plants in PADD3 region) in electricity is presented in Figure 19. The equivalence interval is from 44.90 kg of CO_2 eq. to 57.81 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15%% RAP and 3% RAS need to be at least 16.11% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

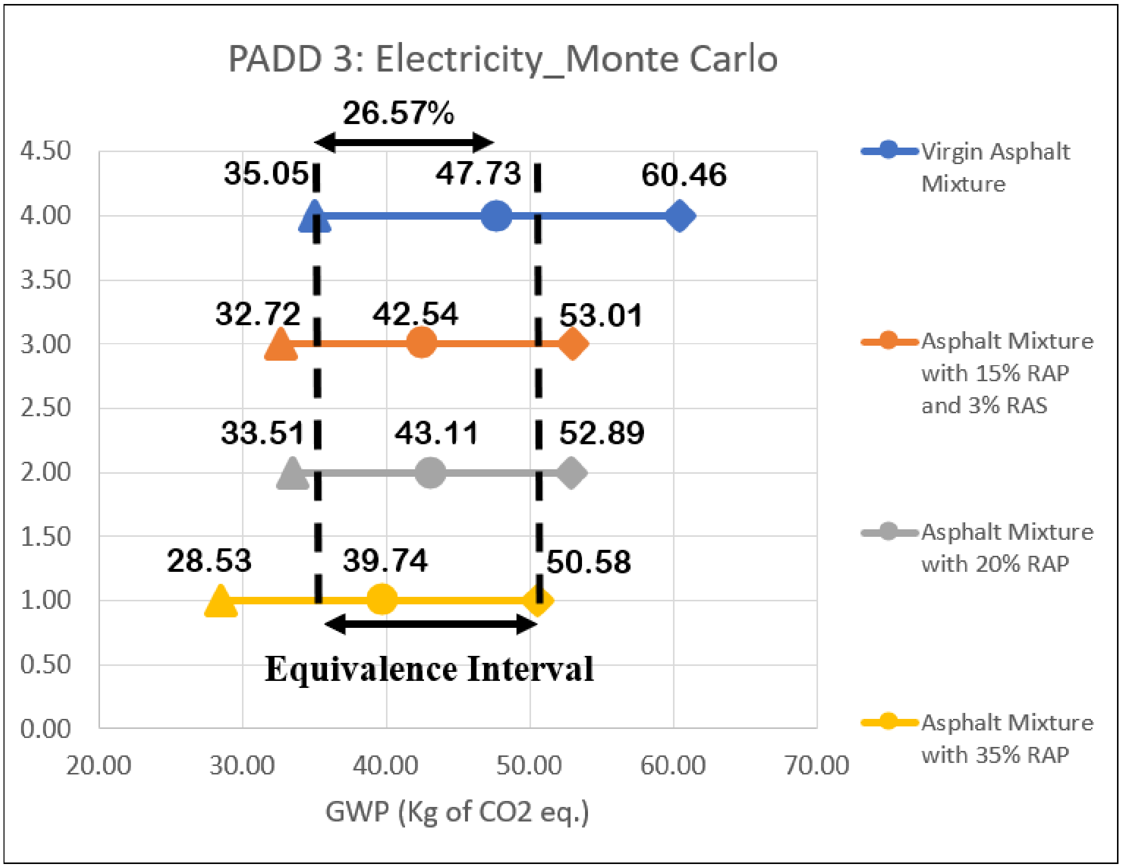


Figure 20. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 3 Foreground Uncertainty in Electricity by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD3 region is presented in Figure 20. The equivalence interval is from 35.05 kg of CO_2 eq. to 50.58 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15%% RAP and 3% RAS need to be at least 26.57% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

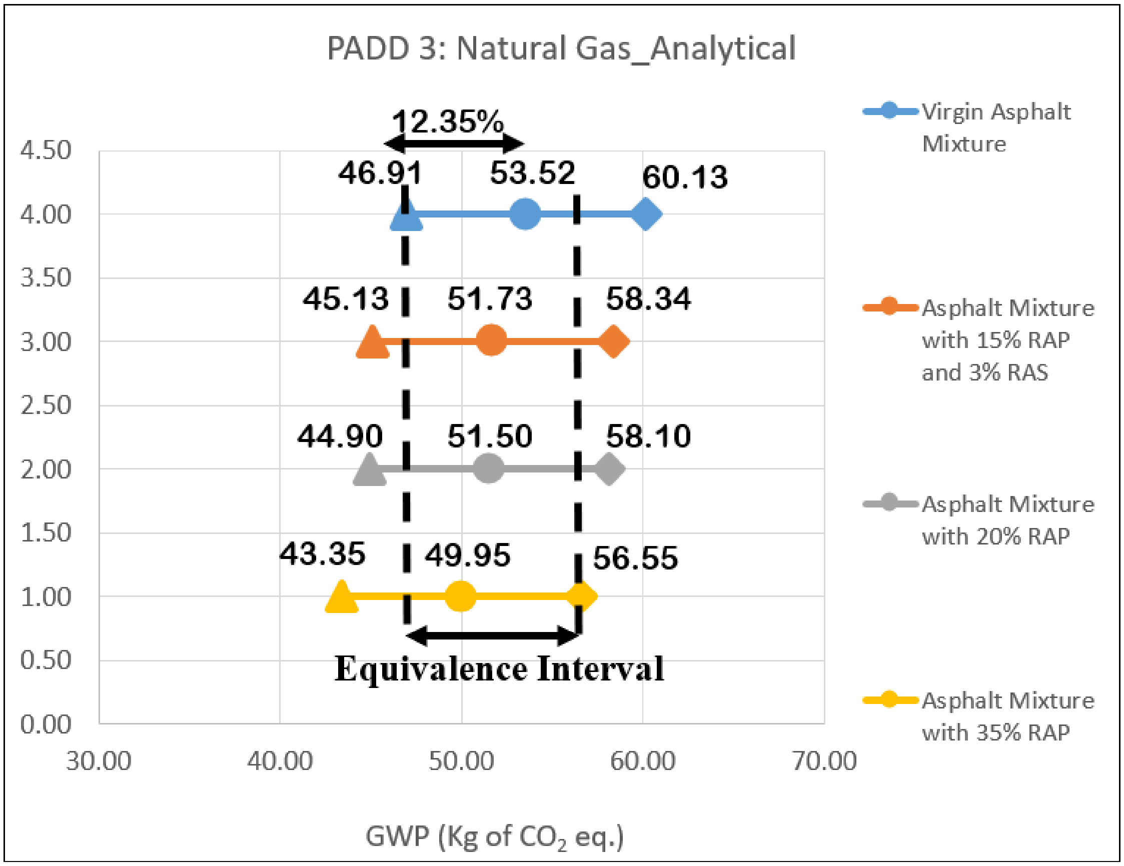


Figure 21. Sensitivity of GWP (Kg of CO_2 eq) to PADD 3 Foreground Uncertainty in Natural Gas by Analytical Method

△ ***CV=-0.25*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.25***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.25 and +0.25 (based on the mean and SD calculated for plants in PADD3 region) in natural gas is presented in Figure 21. The equivalence interval is from 46.91 kg of CO_2 eq. to 56.55 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 12.35% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

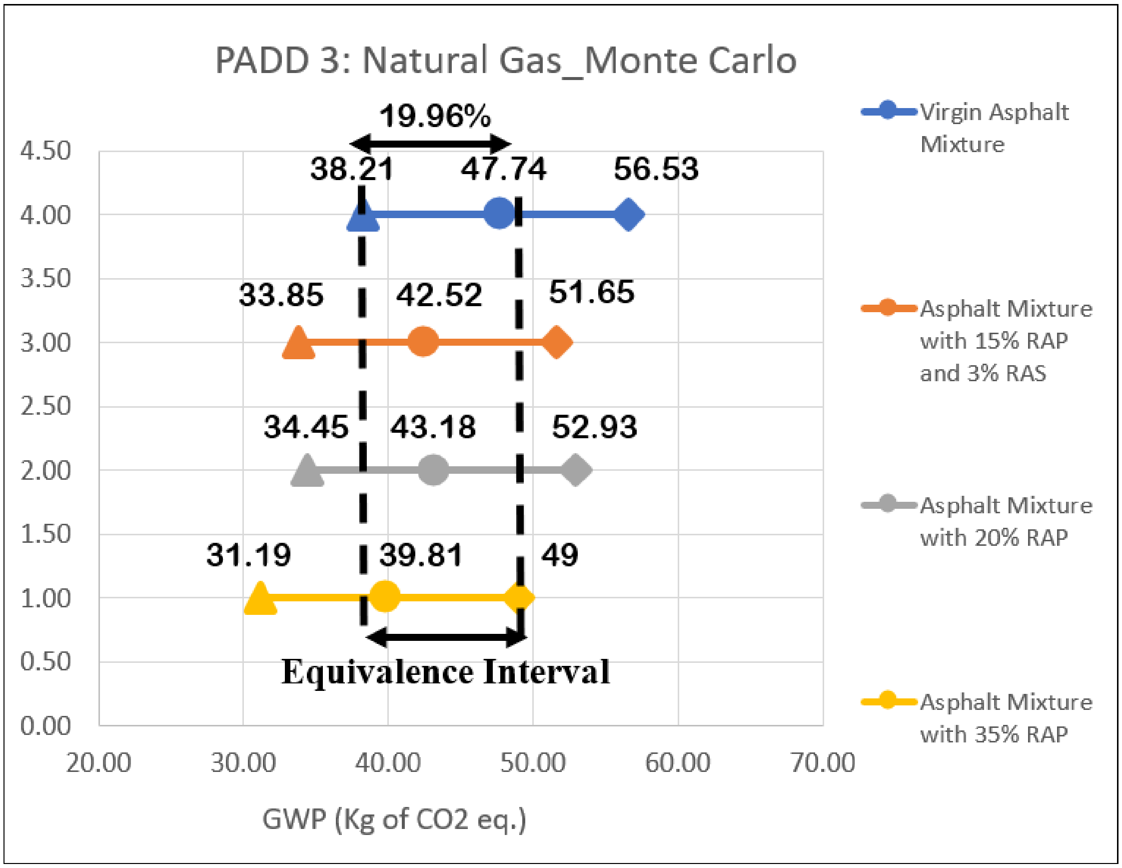


Figure 22. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 3 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of natural gas data in PADD3 region is presented in Figure 22. The equivalence interval is from 38.21 kg of CO_2 eq. to 49 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 19.96% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

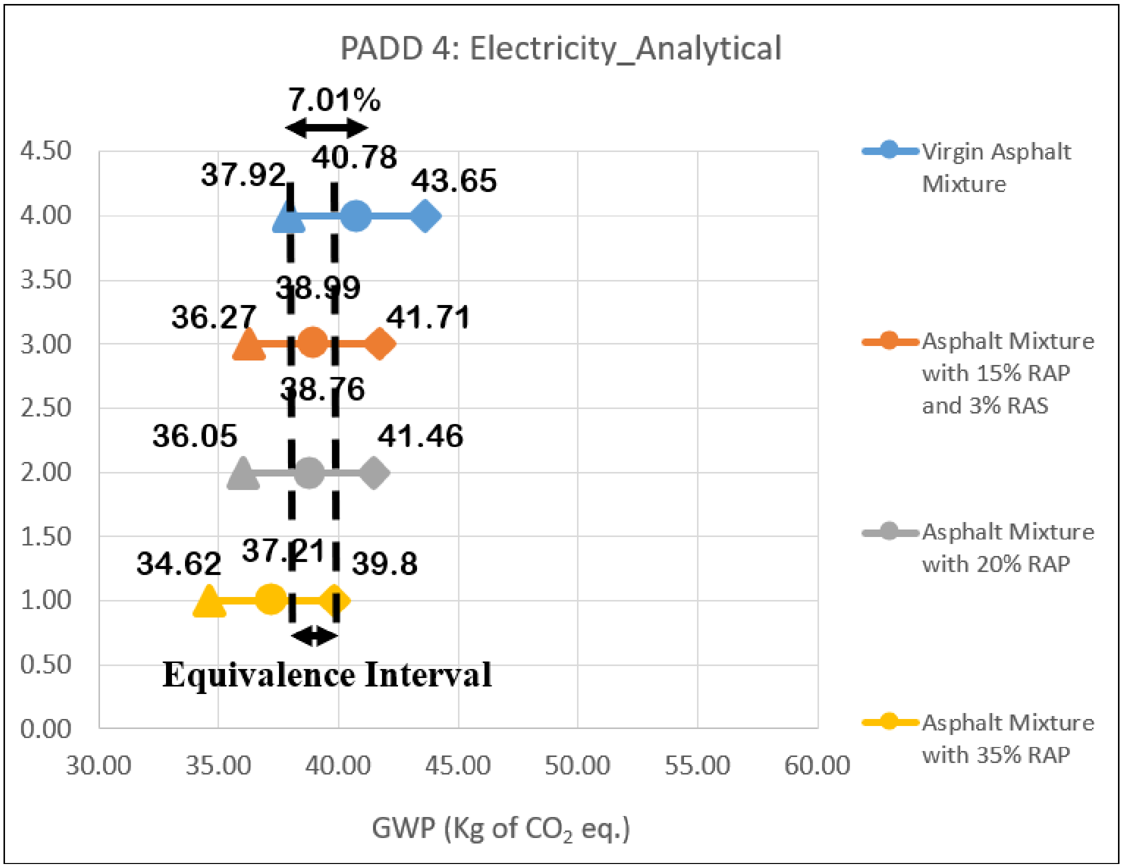


Figure 23. Sensitivity of GWP (Kg of CO_2 eq) to PADD 4 Foreground Uncertainty in Electricity by Analytical Method

△ ***CV=-0.14*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.14***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.14 and +0.14 (based on the mean and SD calculated for plants in PADD4 region) in electricity is presented in Figure 23. The equivalence interval is from 37.92 kg of CO_2 eq. to 39.8 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 7.01% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

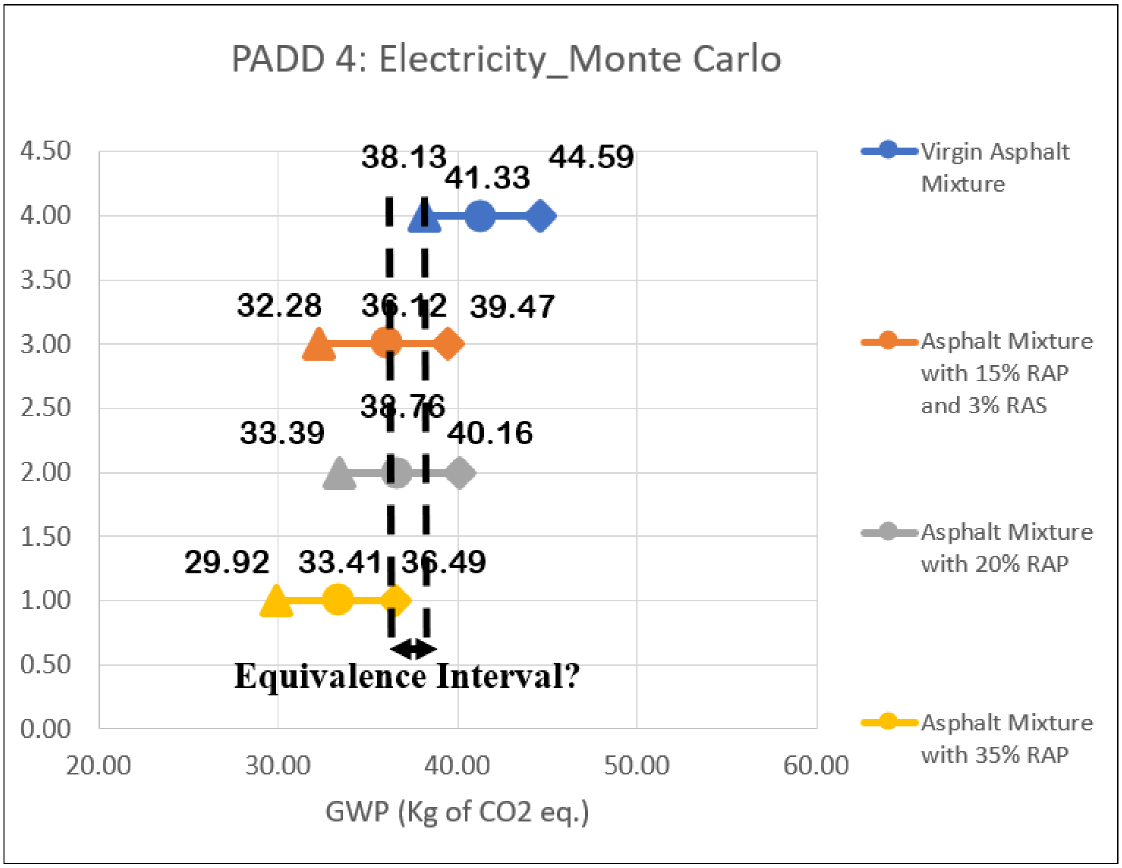


Figure 24. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 4 Foreground Uncertainty in Electricity by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The margins of error interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD4 region is presented in Figure 24. The dispersion of GWP values between alternative asphalt mixtures is not large enough to highlight the equivalence intervals. However, it should be noted that the values of GWP still vary and hence need to be represented by an interval instead of a deterministic value.

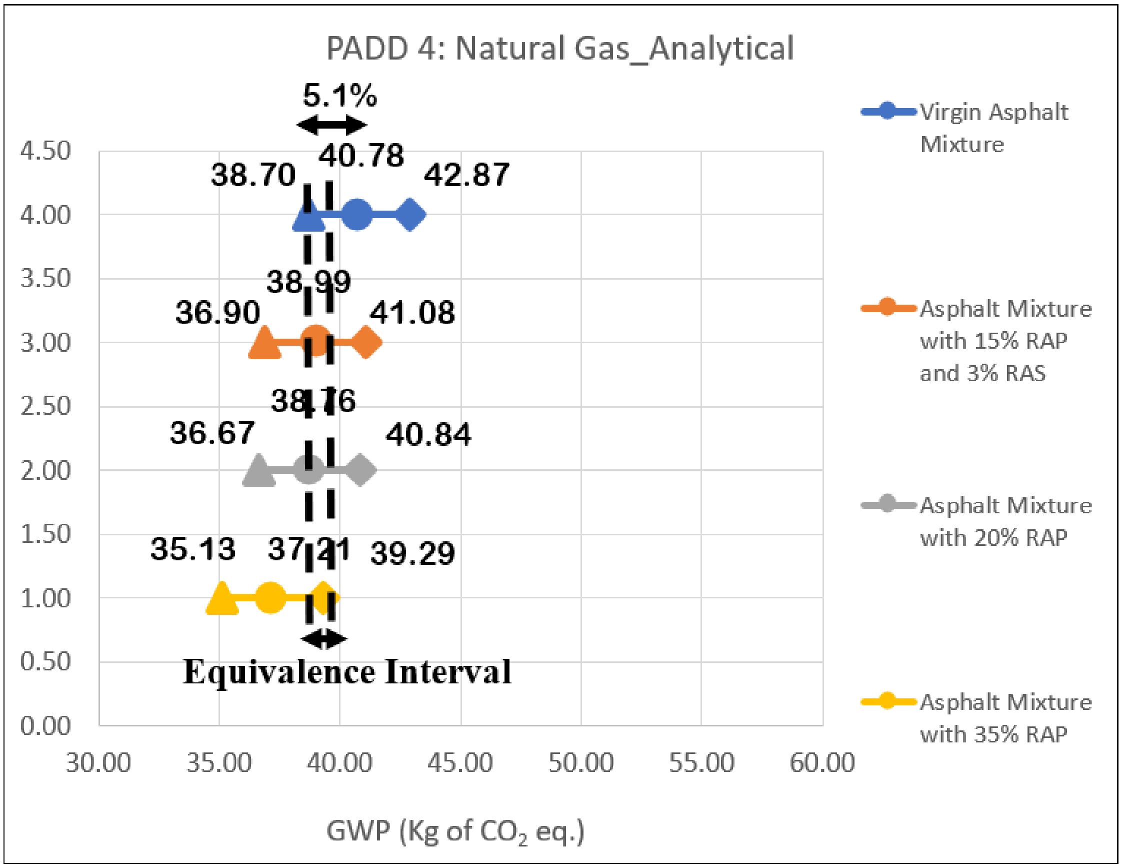


Figure 25. Sensitivity of GWP (Kg of CO_2 eq) to PADD 4 Foreground Uncertainty in Natural Gas by Analytical Method

△ ***CV=-0.1*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.1***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.1 and +0.1 (based on the mean and SD calculated for plants in PADD4 region) in natural gas is presented in Figure 25. The equivalence interval is from 38.70 kg of CO_2 eq. to 39.29 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 5.1% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

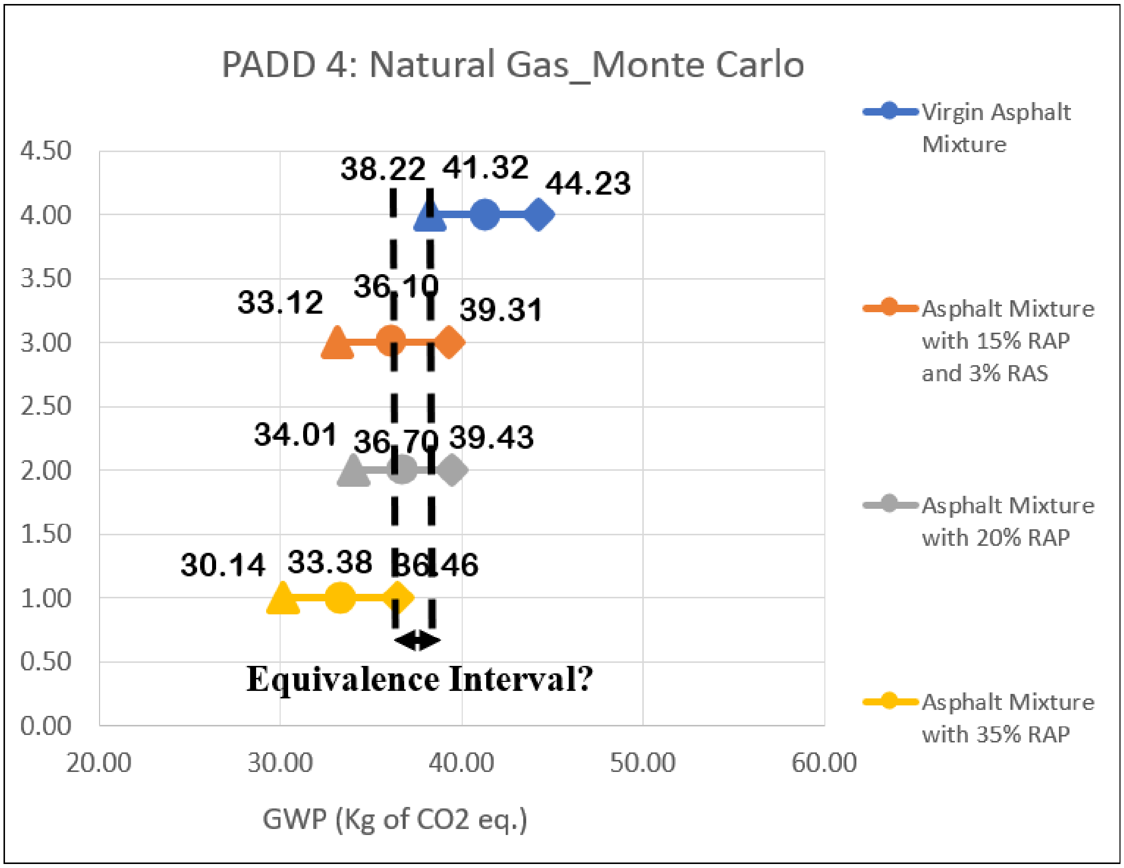


Figure 26. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 4 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The margins of error interval from the Monte Carlo method assuming a normal distribution of natural gas data in PADD4 region is presented in Figure 26. The dispersion of GWP values between alternative asphalt mixtures is not large enough to highlight the equivalence intervals. However, it should be noted that the values of GWP still vary and hence need to be represented by an interval instead of a deterministic value.

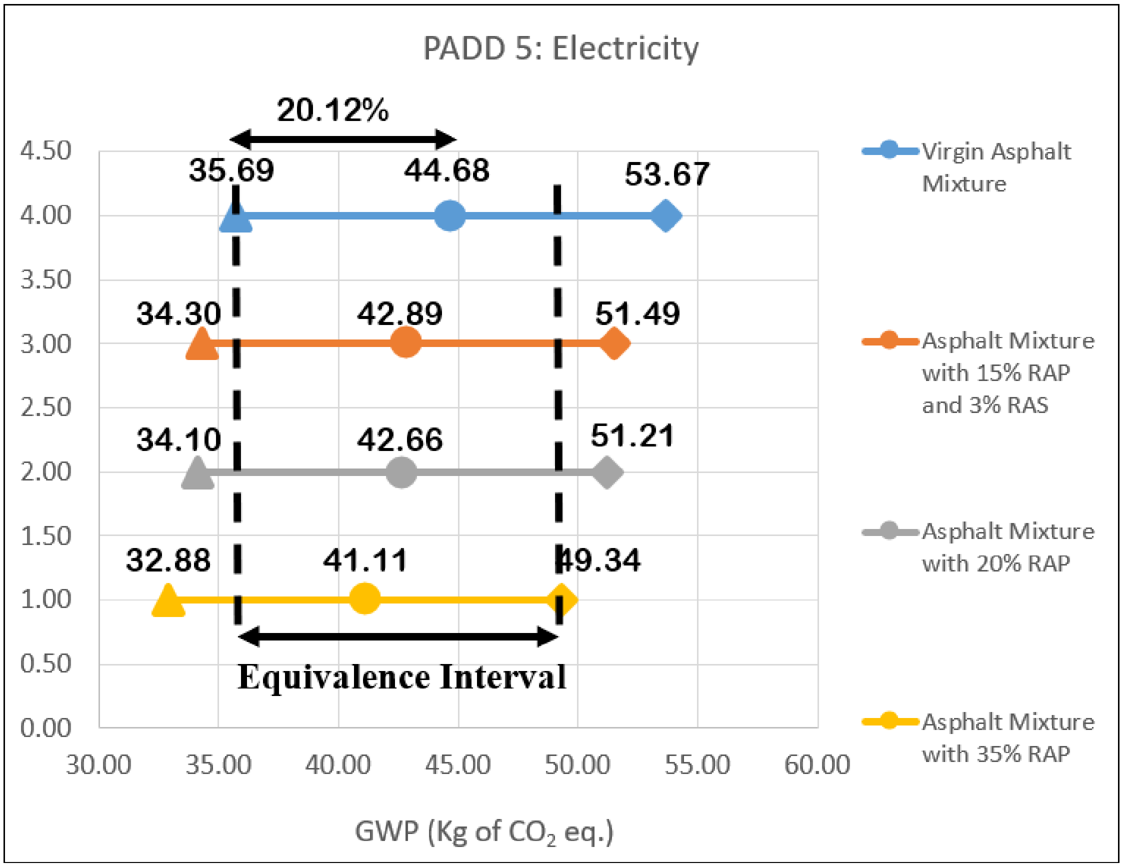


Figure 27. Sensitivity of GWP (Kg of CO_2 eq) to PADD 5 Foreground Uncertainty in Electricity by Analytical Method

△ ***CV=-0.4*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.4***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.4 and +0.4 (based on the mean and SD calculated for plants in PADD5 region) in electricity is presented in Figure 27. The equivalence interval is from 35.69 kg of CO_2 eq. to 49.34 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 20.12% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

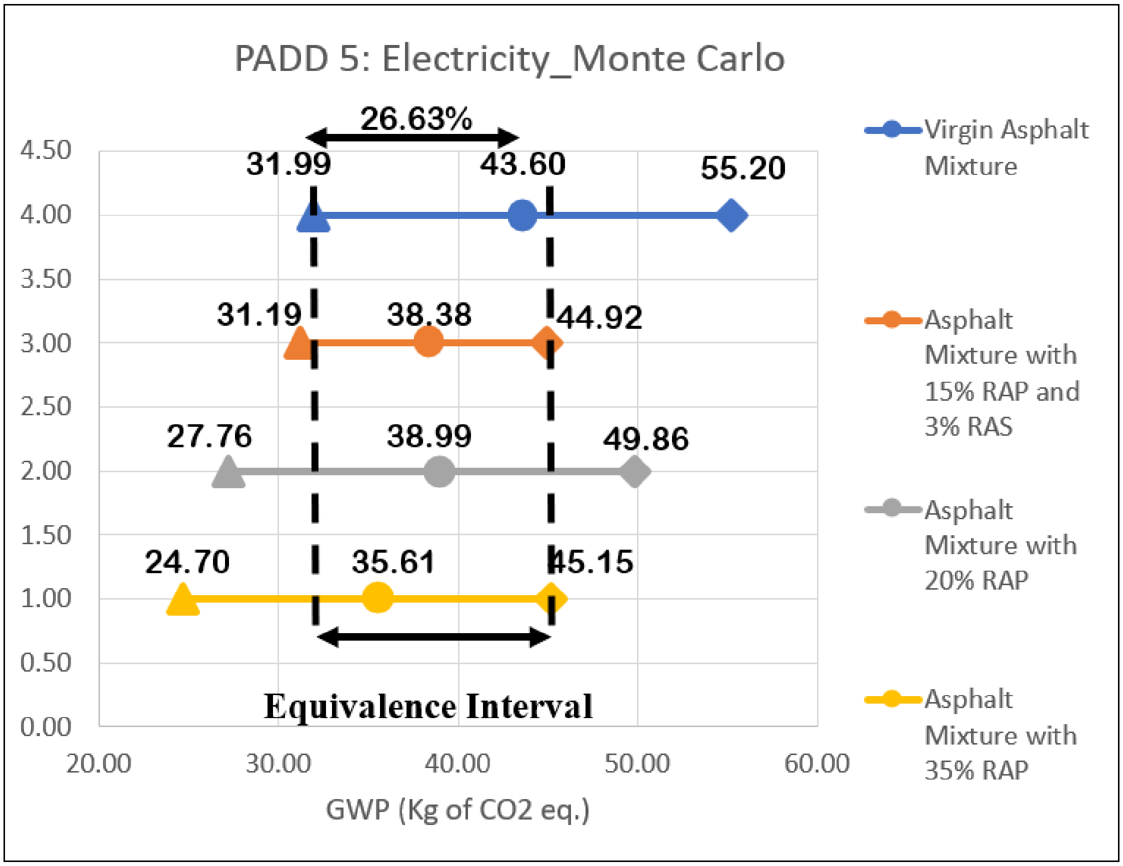


Figure 28. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 5 Foreground Uncertainty in Electricity by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD5 region is presented in Figure 28. The equivalence interval is from 31.99 kg of CO_2 eq. to 45.15 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 26.63% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

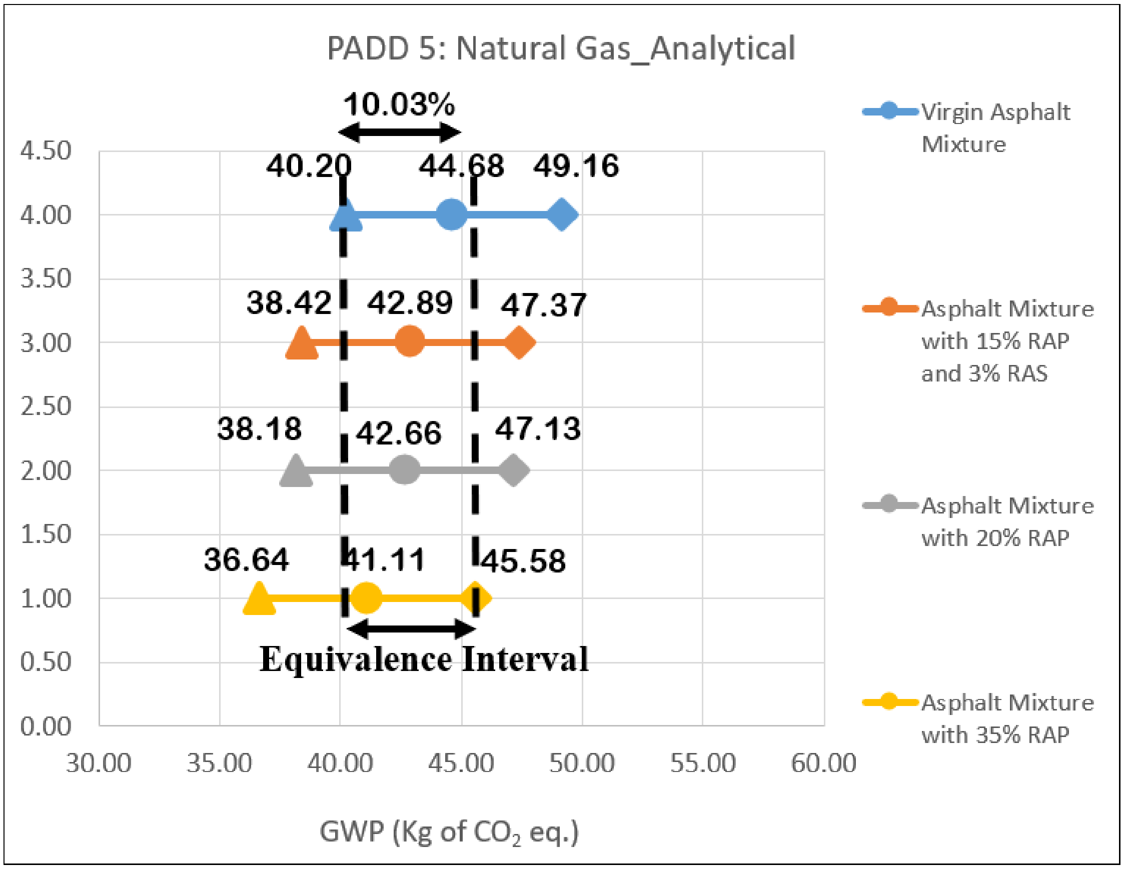


Figure 29. Sensitivity of GWP (Kg of CO_2 eq) to PADD 5 Foreground Uncertainty in Natural Gas by Analytical Method

△ ***CV=-0.18*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.18***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.18 and +0.18 (based on the mean and SD calculated for plants in PADD5 region) in electricity is presented in Figure 29. The equivalence interval is from 40.20 kg of CO_2 eq. to 45.58 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 10.03% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

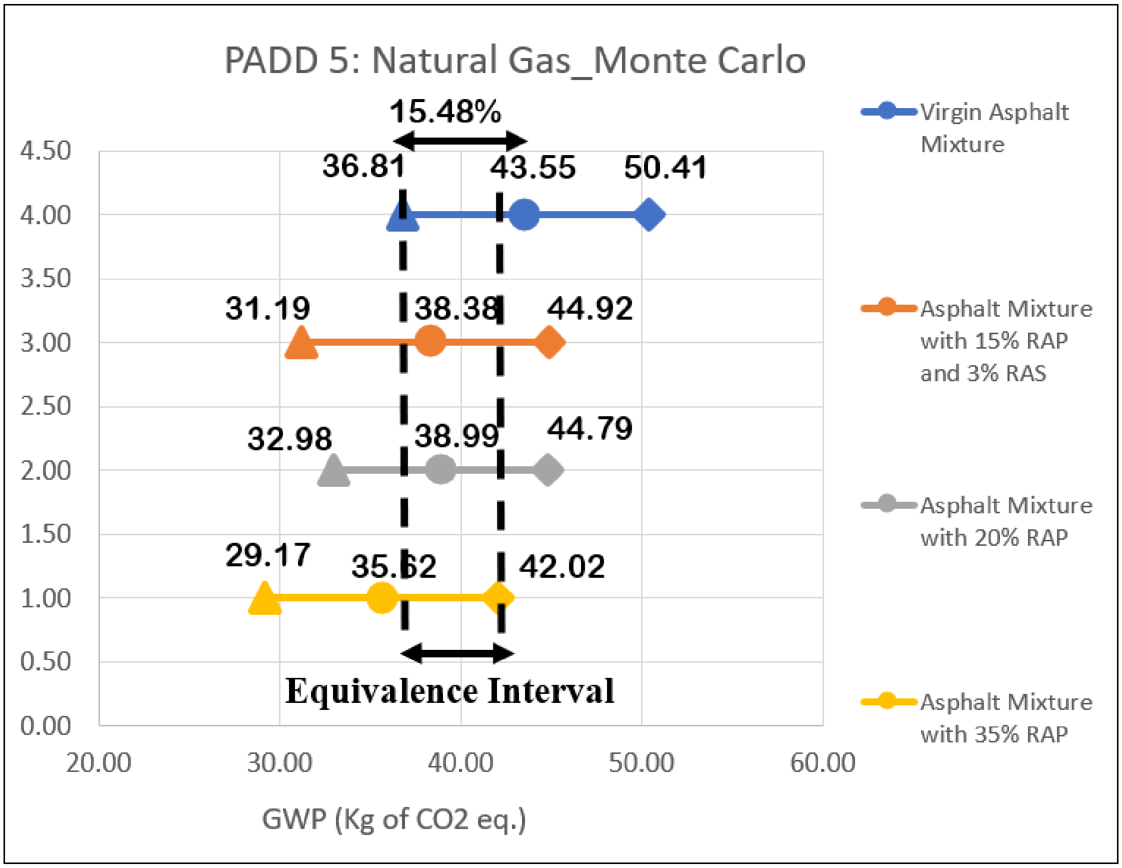


Figure 30. Sensitivity of GWP (Kg of CO_2 eq.) to PADD 5 Foreground Uncertainty in Natural Gas by Monte Carlo Simulation

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of natural gas data in PADD5 region is presented in Figure 30. The equivalence interval is from 36.81 kg of CO_2 eq. to 42.02 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 15.48% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

Applicability of Analytical Method vs Monte Carlo Simulation:

The advantage of analytical methods over stochastic methods is that they can be applied in case of limited knowledge about the uncertainty in the input data. Specifically, in the case of analytical methods, there is no need for a probability distribution to characterize the uncertainty of input parameters. Instead, second moments such as standard deviation, variance, and coefficient of variation are enough to propagate uncertainty. Also, analytical methods do not require considerations of computational efficiency as some of the stochastic methods such as Monte Carlo Simulation do. A disadvantage of the analytical method is that formulating the matrices with a large number of input parameters can be difficult to scale for a large number of parameters.

The suggestion moving forward is to utilize the LCIMs mapped to consistent background data and emphasize collecting empirical data and statistically characterizing distributions that adequately represent foreground data. In turn, these distributions will support the appropriate use of Monte Carlo simulation and avoid unfeasible ranges for consumption variables.

4.2 Significance of Equivalence Intervals at Project Level

It is important to reiterate that the recycled materials such as RAP and RAS are used to replace the virgin aggregate and virgin binder and decrease the amount of GWP as compared to the virgin mixture. However, the range of GWP for which the savings in the GWP because of higher RAP, RAS use may be discounted due to the variation in foreground parameters such as electricity and energy consumption. Mathematically, the equivalence interval refers to overlapping ranges of GWP for the different options when different levels of CV are accounted for. Hence, all the values of GWP within the equivalence interval for a CV in electricity or natural gas can be treated as equivalent for decision-making purposes during material procurement.

This section examines the significance of equivalence intervals by scaling the energy and materials required at a construction project level. The analysis limits the scope to scaling just the energy and materials pertaining to alternative asphalt mixtures placed and does not account for the energy for the operation of construction equipment construction equipment or other materials placed in the base and sub-base. However, these values are of additive nature that can be added as data on the respective entities becomes available. Specifically, the significance is illustrated for an HMA reconstruct project detailed in Mukherjee and Cass, (2011). The project site for HMA reconstruct is located on US-31 and involved *13.08 lane miles* of HMA reconstruction. The amounts of asphalt materials for *13.08 lane miles* of reconstruction were estimated to be *103816 metric tons* as mentioned in the project inventory. Now since the project site falls within PADD 2 (Michigan), the equivalence intervals due to aleatory uncertainties in electricity and natural gas are constructed for the same region. The following equivalence intervals were obtained for *one short ton* of asphalt mixtures:

1. Due to variation in electricity consumption using Analytical: 11.75% (Figure 15)
2. Due to variation in natural gas consumption using Analytical: 11.46% (Figure 17)
3. Due to variation in electricity consumption using Monte Carlo: 7.08% (Figure 16)
4. Due to variation in natural gas consumption using Monte Carlo: 12.37% (Figure 18)

In order to compute the equivalence intervals using analytical method at the project level, the reference product flow in the final demand vector is replaced from *1 short ton* to *103816 metric tons*. A similar process is carried out in OpenLCA and the equivalence intervals are computed using Monte Carlo simulation approach considering the foreground parameters specified in LCIMs for PADD2.

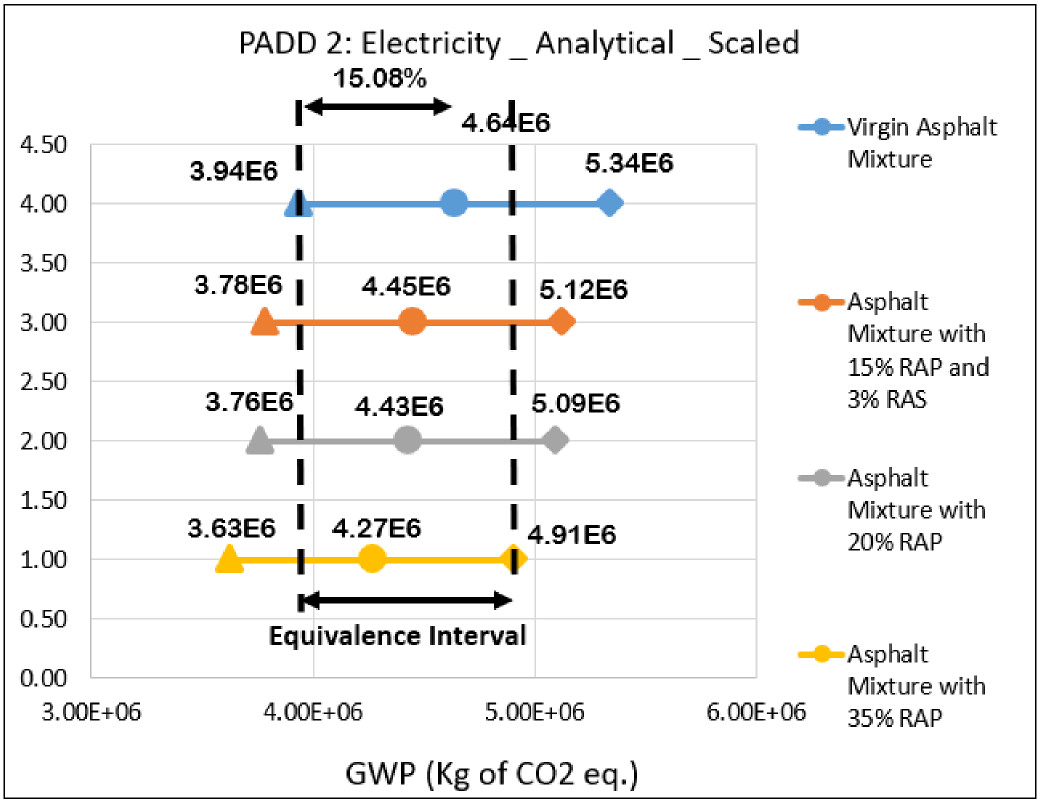


Figure 31. Sensitivity of GWP (Kg of CO_2 eq) to PADD 2 Foreground Uncertainty in Electricity by Analytical Method _ Scaled

△ ***CV=-0.3*** ○ ***Deterministic Outcome*** ◇ ***CV=+0.3***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.3 and +0.3 (based on the mean and SD calculated for plants in PADD2 region) in electricity is presented in Figure 31. The equivalence interval is from 3.94E6 kg of CO_2 eq.

to 4.91E6 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 15.08% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the electricity flow.

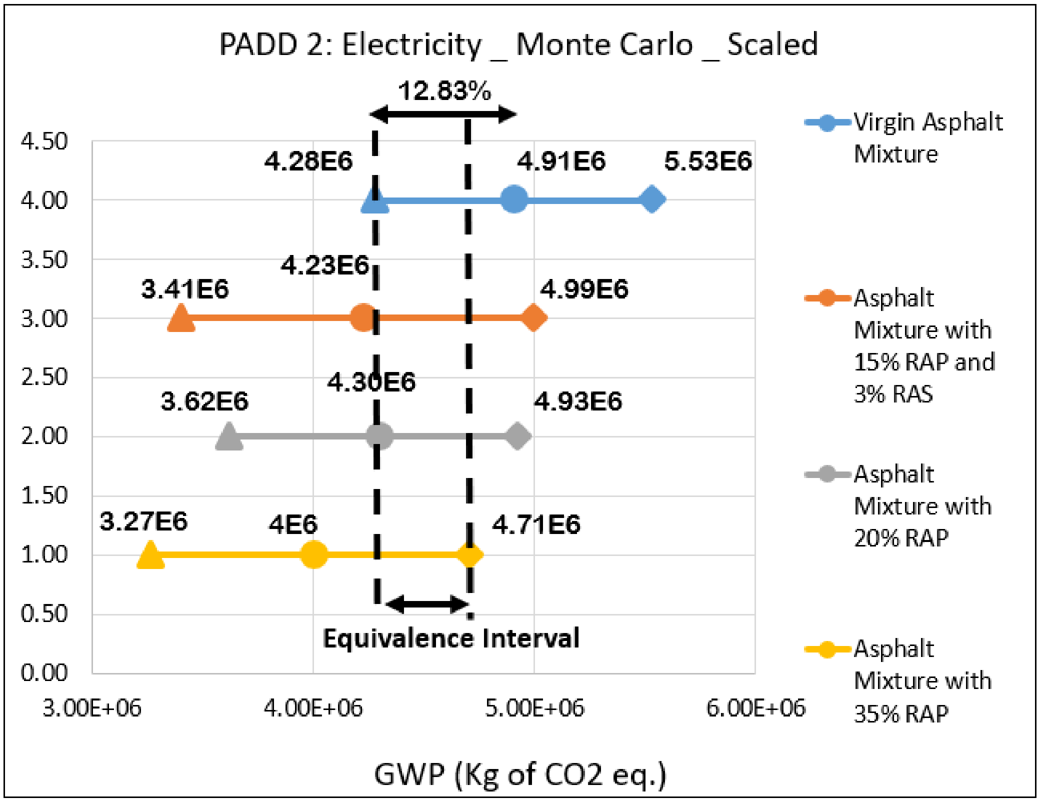


Figure 32. Sensitivity of GWP (Kg of CO2 eq) to PADD 2 Foreground Uncertainty in Electricity by Monte Carlo Method _ Scaled

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD2 region is presented in Figure 32. The equivalence interval is from 4.28E6 kg of CO_2 eq. to 4.71E6 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 12.83% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

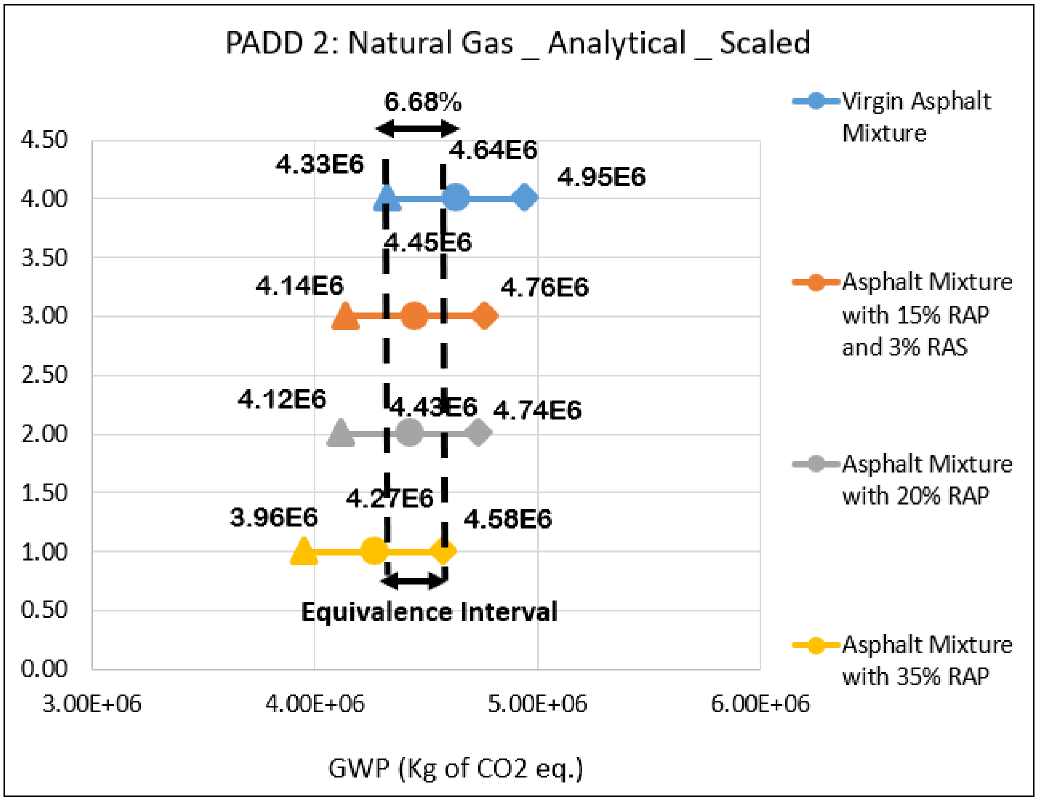


Figure 33. Sensitivity of GWP (Kg of CO2 eq) to PADD 2 Foreground Uncertainty in Natural Gas by Analytical Method _ Scaled

△ ***CV= -0.12***

○ ***Deterministic Outcome***

◇ ***CV= +0.12***

The equivalence interval from the analytical method for GWP at the threshold CV's of -0.12 and +0.12 (based on the mean and SD calculated for plants in PADD2 region) in natural gas is presented in Figure 33. The equivalence interval is from 4.33E6 kg of CO_2 eq. to 4.58E6 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 6.68% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

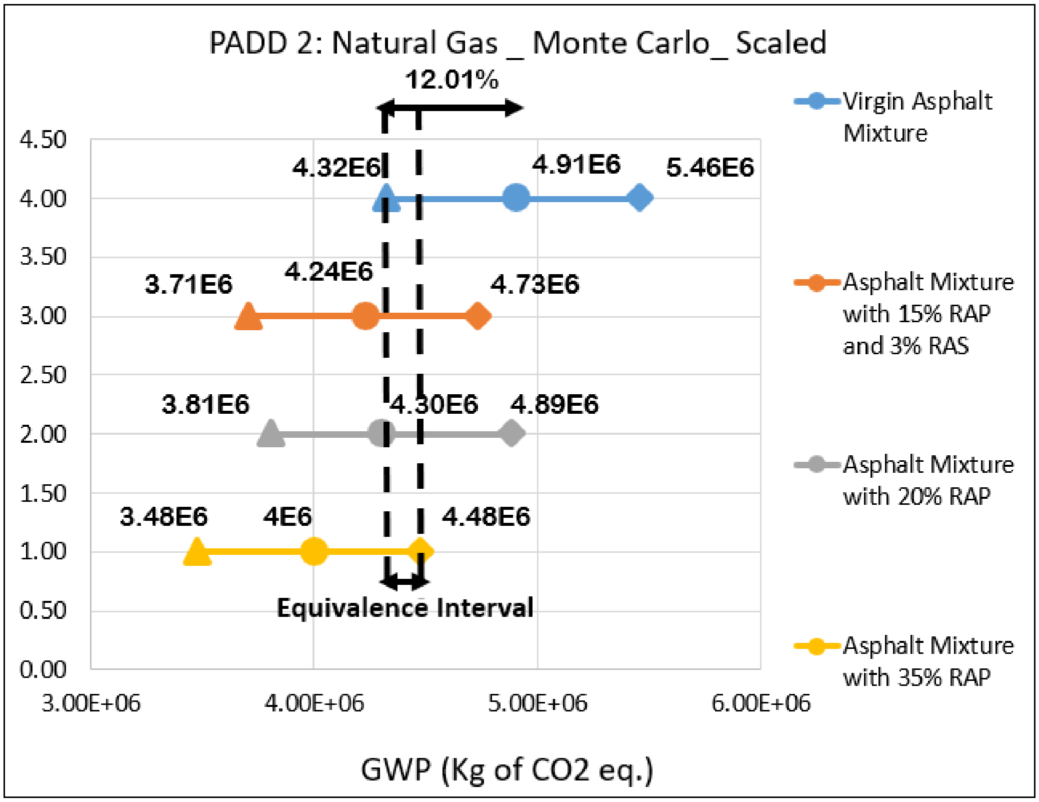


Figure 34. Sensitivity of GWP (Kg of CO2 eq) to PADD 2 Foreground Uncertainty in Natural Gas by Monte Carlo Method _ Scaled

△ ***Minimum*** ○ ***Mean*** ◇ ***Maximum***

The equivalence interval from the Monte Carlo method assuming a normal distribution of electricity data in PADD2 region is presented in Figure 34. The equivalence interval is from 4.32E6 kg of CO_2 eq. to 4.48E6 kg of CO_2 eq. This implies that, despite the addition of recycled materials, the GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 12.01% less than the 0% RAP mixture, for them to be considered environmentally sustainable due to the uncertainty in the natural gas flow.

The specific insights from evaluation of the equivalence intervals at a project level are:

1. The numerical value of equivalence intervals is context-specific and needs to be evaluated based on change in the value of reference product flow. For example, the equivalence interval for *one short ton* and *103816 short tons* due to the same variation in electricity consumption are 11.75% and 15.08% respectively from the analytical approach.
2. The percentage decrease in GWP to fall beyond the equivalence intervals may seem miniscule for *one short ton* of asphalt mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS. However, this percentage decrease amounts to be

significant when considering the amount of asphalt mixtures required at a project level. For example, the equivalence interval for *103816 short tons* of asphalt mixture due to variation in electricity is 15.08% (presented in Figure 31). This means that GWP from mixtures with 20% RAP, 35% RAP and 15% RAP and 3% RAS need to be at least 6.99E5 Kg of CO_2 eq. (numerical value indicating 15.08%) less than the virgin mixture to be considered environmentally sustainable due to variation in electricity.

Hence, the use of recycled materials may be considered environmentally sustainable only when the percent decrease in GWP falls beyond the equivalence interval and not just by the notion that they replace virgin materials. The use of recycled materials without accounting for the variation in foreground parameters such as electricity and energy may lead to erroneous decision-making.

4.3 Applicability of Equivalence Intervals

The contribution of this dissertation is the method for developing equivalence intervals, an illustration of what data is necessary to implement it, and how it can be used in pavement design decision-making. The development of equivalence intervals discussed in this dissertation will enable the appropriate selection of mixtures when considering trade-offs between different aspects of sustainability such as environmental impacts, performance and cost of a product.

Mukherjee, (2016) collected the foreground data from 40 plants (approximately 2% of the total asphalt mixture plants in the United States) and reported 95% confidence interval values for electricity and energy. Based on this study, this dissertation characterized the aleatory uncertainty due to diurnal variations in electricity and natural gas consumption for asphalt mixture production. Next, this aleatory uncertainty was propagated for four asphalt mixtures containing varying amounts of RAP and RAS. While this illustrates the approach to develop equivalence intervals, the intervals developed themselves have limited applicability because aleatory uncertainty from 40 plants is not adequately representative of the variability in electricity and natural gas across different regions of the United States. The applicability of equivalence intervals is relevant only after similar analyses is conducted on a statistically significant sample of plants and mixtures. ***Hence, the equivalence intervals communicated in this dissertation should not be generalized i.e., the sample results should not be construed to imply that the use of RAP is not beneficial environmentally in an asphalt mixture, but rather that if the underlying uncertainty is not characterized correctly, there could be a miscommunication about the benefits of using recycled materials in the product.***

In future, the method of developing equivalence interval can be employed after developing 95% confidence interval values using statistically significant plant-specific and mixture-specific foreground data, collected for different asphalt mixtures. This concept is graphically represented in Figure 35.

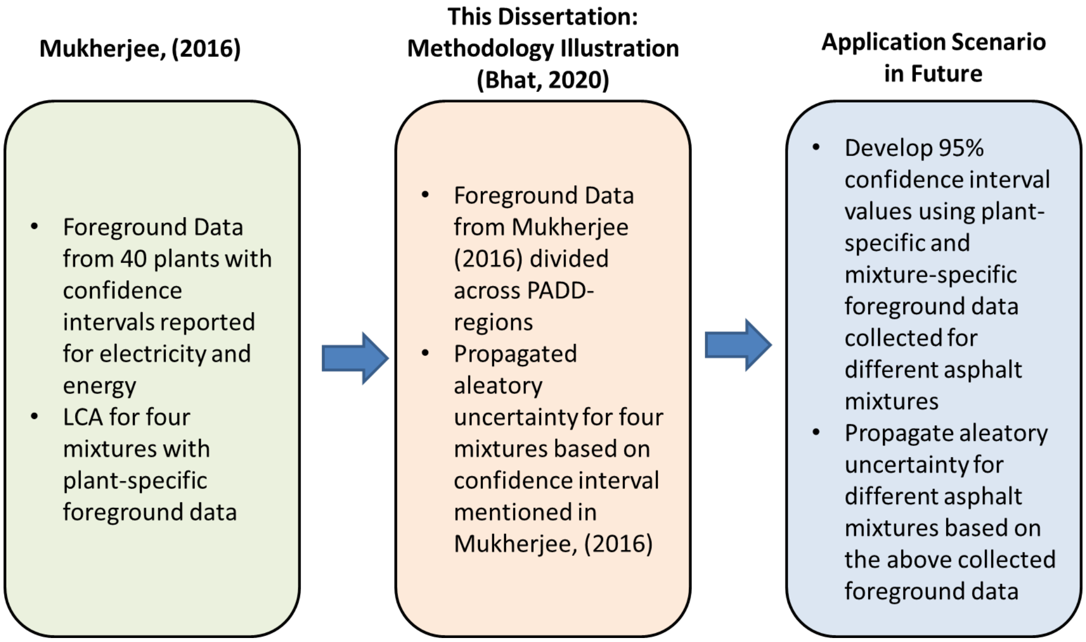


Figure 35. Application of Equivalence Intervals

4.4 Epistemic Uncertainty

The margins of error within quantified potential environmental impacts is not only a function of aleatory uncertainty within the foreground data but may also be caused by using different background data. This section discusses the range of potential environmental impacts as an artifact of background data selection using LCIMs. The development of a comprehensive pavement LCA information model is a long-term goal and must include stakeholder involvement in appropriate identification of all parameters. At this time the scope of this effort is being limited to the cradle-to-gate asphalt mixtures to address the immediate needs for creating consistent LCA for EPD generation for pavement material LCAs. Specifically, the illustration highlights the usefulness of LCIMs in setting up product systems for different background data sets and identifying the impact of inconsistent use of background data. An information model for a cradle-to-gate LCA for an asphalt mixture reflects:

i. All the processes and flows in the asphalt mixture system boundary and their relationships as defined by the process and lineage ontologies,
ii. The background data sets for upstream processes such as electricity, fossil fuels and transportation, and
iii. Parameters characterizing foreground data such as energy, aggregate and asphalt binder consumption during the asphalt production process.

LCIMs are illustrated to check the sensitivity of Global Warming Potential (GWP) (a mid-point indicator computed using TRACI impact assessment method) to background data selection for one short ton declared unit of each of the alternative asphalt mixtures. The results of sensitivity analysis are presented in Figure 31. The foreground data for sensitivity analysis is obtained from Mukherjee, (2016), an ISO 14040 compliant LCA study supporting the PCR for NAPA EPD program. ***The sensitivity analysis illustrated that the decrease in the GWP due to the use of recycled materials in asphalt mixtures may be offset due to epistemic uncertainty caused by using different background datasets. For example, the GWP for asphalt mixture with 35% RAP may be higher than the virgin asphalt mixture if the information model for the former mixture consists of a different asphalt binder background data (Asphalt Institute, 2019) than the latter (Mukherjee, 2016), assuming that all the other parameters are constant.***

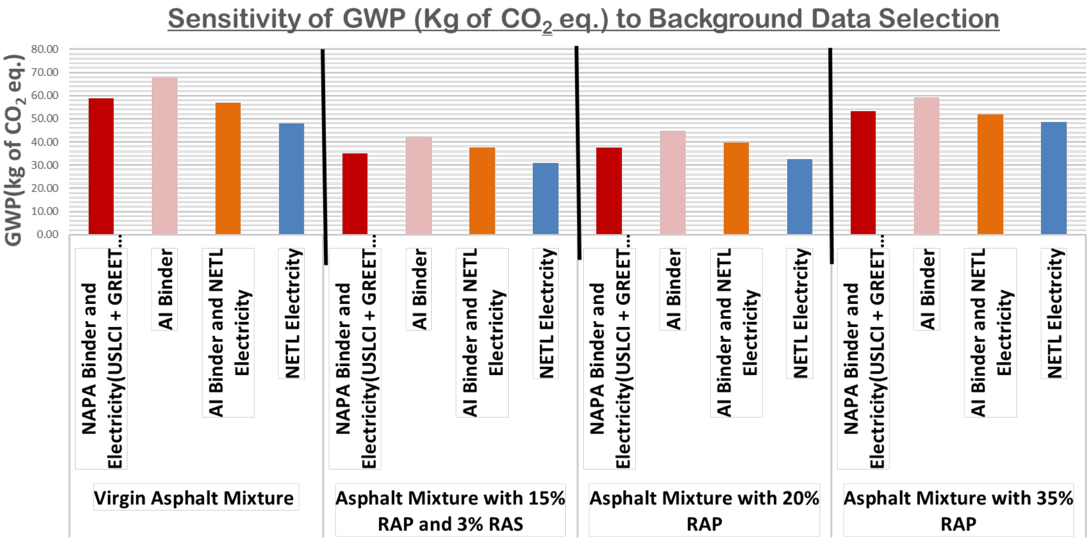


Figure 36. Illustration of Epistemic Uncertainty Results

4.5 Protocol (Allocation) Uncertainty

Asphalt binder, a key component in asphalt mixture, is a co-product of crude oil refining that produces as diesel, gasoline, kerosene, jet fuel oil, naphtha and others. ISO Standard 14044 Clause 4.3.4 details on "allocation" within life-cycle inventory analysis to partitions 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. ISO Standard 14044 Clause 4.3.4.2 prioritizes co-product allocation through the following step wise procedure.

i. "*Wherever possible, allocation should be avoided by*
    - *Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to sub-processes*
    - *Expanding the product system to include additional functions related to the co-products*

ii. *When allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them. This type of allocation can* *be done based on the mass or energy of different products coming out of a multi-functional process.*

iii. *When physical relationship alone cannot be considered or used as the basis for allocation, the inputs shall be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products*".

This dissertation furthers the allocation approach adopted by Mukherjee, (2016) that was originally coined by Yang, (2014). The economic allocation factors and mass yield fractions for different PADD regions are adopted from Yang, (2014) and the economic allocation coefficients presented in Table 1 are calculated.

Table 3. Economic Allocation Coefficients for Asphalt Binder

Co-Products	Economic Allocation Coefficient				
	PADD1	PADD2	PADD3	PADD4	PADD5
Liquefied Petroleum Gas	0.05	0.04	0.02	0.03	0.03
Finished Motor Gasoline	0.52	0.52	0.47	0.47	0.52
Kerosene	0.11	0.11	0.09	0.11	0.00
Distillate Fuel Oil	0.24	0.24	0.25	0.25	0.27
Residual Fuel Oil	0.03	0.03	0.03	0.02	0.04
Special Naphtha's	0.05	0.05	0.05	0.00	0.05
Lubricants	0.14	0.14	0.16	0.00	0.16
Petroleum Coke	0.00	0.00	0.01	0.00	0.01
Asphalt and Road Oil	0.02	0.02	0.02	0.01	0.02

The coefficients presented in Table 3 are appropriately assigned to asphalt binder background flow and relevant foreground parameters for different PADD regions within the LCIMs and the sensitivity of GWP to different economic allocation coefficients are calculated. The sensitivity of GWP to economic allocation coefficients is presented in Figure 33. The results showed that the GWP is sensitive to the economic allocation coefficient for asphalt than the other products and the value of GWP for PADD 4 varied from the deterministic GWP values.

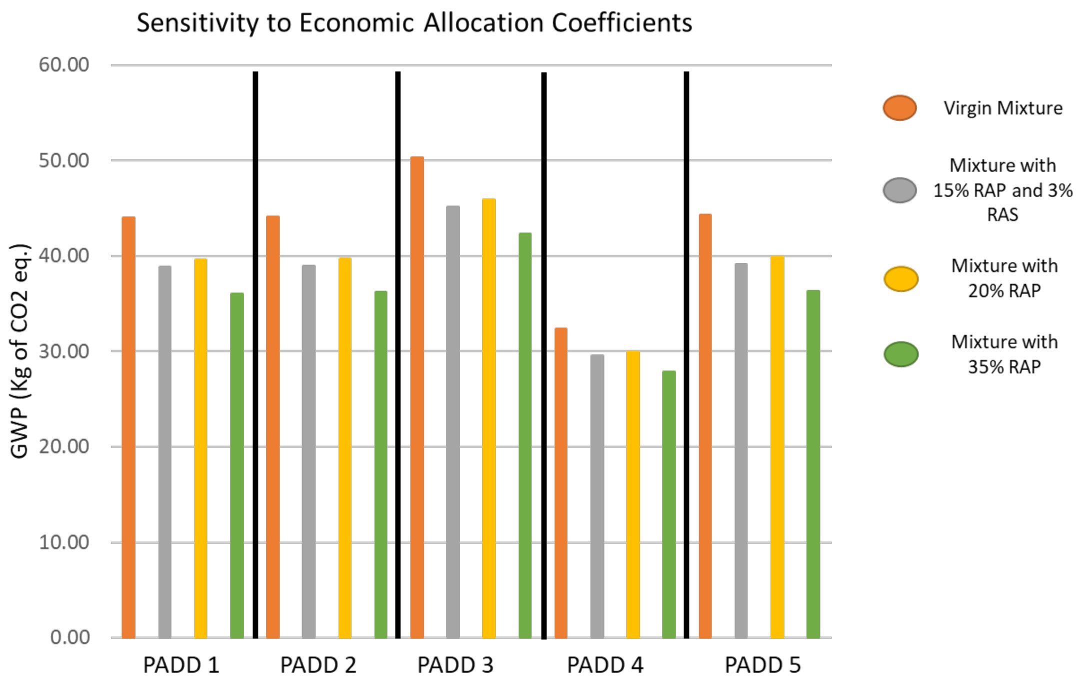


Figure 37. Sensitivity to Economic Allocation Factors

The purpose of assessing the uncertainty due to economic allocation coefficients is to highlight the margin of error in quantified potential environmental impacts. This uncertainty presses the need to allocate the impacts due to crude oil refining based on actual physical relationships than highly sensitive parameter such as economy. It is because of this reason that the economic allocation is the least preferred method as per the ISO Standard's hierarchy for allocation. Recently, different scenarios of physical allocations have been proposed in the LCA study on asphalt binders conducted by Asphalt Institute (Asphalt Institute, 2019), however this is not the focus of this dissertation.

5 Conclusions

The research presented in this dissertation is motivated by the need for a standard specification of datasets, products and processes for pavement LCA to ensure transparency and verifiable quality of background Life Cycle Inventories (LCI). In addition, the dissertation identified the need to communicate potential environmental impacts with margins of error due to different uncertainties. Specifically, the contributions of this dissertation are:

1. Develops a formalism through an ontology-based approach to specify the relationships between pavement LCA flows and processes.
2. The data structures are also mapped onto background LCI, and foreground parameters that are used in pavement LCA, to create parametric information models that we refer to as Life Cycle Information Models (LCIM), and the LCIMs can be used "building blocks" for pavement LCA.
3. As LCA software tools are developed to support decision-making for departments of transportation, the ontological representation of the pavement domain can serve as a specification outlining a common set of protocols.
4. Develops equivalence intervals to identify the values of GWP due to the Coefficient of Variation (CV) in electricity or natural gas that can be treated as equivalent for decision-making purposes during material procurement.
5. Examines the sensitivity of GWP due to the selection of different background data as well as due to the variation of economic allocation coefficient in different regions.

The following sections provide concluding remarks for each of the contributions.

5.1 Concluding Remarks on Life Cycle Information Models

As a first step to formalize the digital information models for pavements, an ontology based representation covering all the life cycle stages apart from use stage is presented. This ontology is then manually transferred to OpenLCA to compute Life-Cycle Information Models (LCIMs). LCIMs discussed in this dissertation consists of the following to ensure reliable and consistent inclusion of potential environmental impacts within decision-making:

i. Hierarchical data structure based on an ontology for consistent representation, sharing and management of pavement domain knowledge across all the life-cycle stages apart from the use stage. This work meets the need for a formal, reusable data structure detailing entities within the pavement LCA system boundary and highlighting the relationships between these entities.
ii. Consistent mapping of data structure to publicly available background datasets achieved through the collaboration with the LCA Commons

iii. Parameterization to encourage pavement LCA stakeholders such as material producers, design decision-makers to develop context-specific LCI models. This is possible through LCIMs by inputting process-specific foreground data to characterize flows that are already mapped to the consistent background data.

Beyond pavement LCA, this research has general implications to the field of LCA. As LCA information is being considered for public procurement, inconsistent use of background data sources may cast doubt on outcomes, and eventually hinder the meaningful use of LCA in supporting decision-making.

LCIM implementation will encourage LCA practitioners to spend their efforts in collecting high quality foreground data to populate the parameters, while depending on the modeled structure to ensure consistency of the process relationships and reliability of background LCI. This shift of focus towards collecting high quality foreground data with consistent use of background data provides an opportunity to develop equivalence intervals based on the actual collected foreground data as well as examine the sensitivity of background data.

5.2 Concluding Remarks on Uncertainty Analysis

The dissertation discussed the variation in GWP due to different kinds of uncertainties. Specifically, the dissertation discussed equivalence intervals due to aleatory uncertainty for alternative hot-mix asphalt mixtures containing varying amounts of RAP and RAS. These equivalence intervals are established by propagating parameter uncertainties within input foreground data for electricity and natural gas using both the analytical method by Heijungs and Suh, (2002) in an OpenLCA technology agnostic manner and by Monte Carlo Simulations using LCIMs developed in OpenLCA. An important revelation from the aleatory uncertainty analysis is that the equivalence intervals are an artifact of the foreground data with the variations in the data than the methodology used to propagate uncertainty analysis. Hence, more focus should be given in future to standardize the collection of foreground data with diurnal variations using LCIMs.

In addition, the dissertation discussed the sensitivity of GWP due to selection of background data for electricity and asphalt binder. An outcome of this analysis was that the reduction in the value of GWP is not just the function of amount of virgin materials replaced but also on the selection of a background data flow. The sensitivity of GWP due to variation in economic allocation coefficients for different PADD regions showed the need to allocate the impacts due to crude oil refining based on actual physical relationships than highly sensitive parameter such as economy. LCIMs provided the digital infrastructure to examine the sensitivity due to both the background data selection as well as due to the variation in economic allocation coefficients.

5.3 Limitations

The parameterized models are developed only for asphalt mixtures and not for the entire pavement LCA system boundary. The propagation of parameter uncertainty does not consider the correlation between different product flows within asphalt mixture product system. This might over or under-estimate the margins of error between alternative asphalt mixtures. Both these limitations are a function of the availability of reliable data and can be resolved in the future as more data becomes available. The development of ontology is limited to representation only at this time and the ontology is not capable for deductive reasoning. However, this is possible during the implementation of the model through interactions between the user and the ontology to define specific instances.

5.4 Scope for Future Research

The scope for future research is divided into methodological opportunities and implementation opportunities. It should be noted that these two issues may be inter-related however the distinction is established to provide detailed description of aspects within each of these.

5.4.1 Methodological Opportunities

As a first step to move towards digital information models for pavement LCA domain, this dissertation uses ontology for representation purposes only. The representation may be furthered in future by developing a user interface to input pavement design aspects in the front end and embedding pavement domain and LCA domain specific rules at the back end. The pavement domain rules may include design thresholds such as preferred thickness of various layers for a specific type of a pavement or threshold for components of a mixture design if decision-making is pertinent to the procurement stage. The LCA domain rules may be defined as abstract as discussed in Janowicz et al., (2015) to identify flaws in defining a reference product or appropriately defining flows for entities within the product system. The development of domain-specific rules within the ontology will facilitate reasoning and highlight any errors in defining a problem statement by the user.

Further, this robust system of ontology may be linked with the already existing LCA computationalism of OpenLCA to develop an automated workflow for integrating sustainability assessment into parametric part design. The limitations identified from the data quality assessment results highlight the need to improve the definition of meta-data, include regional data parameters. This improvement may be achieved by incorporating data available through different platforms such as fossil fuel data from GREET (Argonne GREET Model, 2019) hosted by the Argonne National Laboratory and electricity data from Mix Grid Explorer (Energy Analysis, 2020) by the National Energy Technical Laboratory. However, the continuous improvement and updating of LCA Commons requires funds from the downstream users of these background datasets.

5.4.2 Implementation Opportunities

The life cycle information models consisting of the recent set of background datasets and foreground parameterization will be directly used in the revision of LCA study supporting PCR for the EPD program hosted by the National Asphalt Pavement Association (NAPA). The research discussed in the dissertation is timely given that the States of California, Arizona, Minnesota, and Illinois and the respective state Departments of Transportation (DOT) are looking at the feasibility of incorporating LCA outcomes communicated through EPDs within procurement decision-making (Mukherjee and Miller, 2019). The LCIMs provide a potential opportunity for researchers to map and link these to design data models from different system platforms such as AASHTOWare's Pavement-ME. In the near future, the suitability of LCIMs will be tested for three case studies to be conducted with Arizona state DOT, Minnesota state DOT and Illinois Tollway.

Also, the illustration of LCIMs is limited to cradle to gate asphalt mixtures and there is a scope to cover the complete cradle to grave system boundary in the future. This is particularly important to get a holistic overview on the trade-offs between different aspects of sustainability such as performance criteria and costs along with potential environmental impacts during decision-making (Bhat and Mukherjee, 2020).

6 Reference List

1. Anl.gov. 2019. *Argonne National Laboratory Homepage | Argonne National Laboratory*. [online] Available at: <https://www.anl.gov/> [Accessed 8 April 2019].
2. Asphalt Institute's LCA Study on Asphalt Binders | Asphalt Institute. Available at: http://www.asphaltinstitute.org/engineering/lca-study-on-asphalt-binders/ (accessed Mar 17, 2020).
3. Asphaltpavement.org. 2019. *National Asphalt Pavement Association (NAPA) EPD Program*. [online] Available at: <http://www.asphaltpavement.org/EPD> [Accessed 6 April 2019].
4. *ASTM E3012 - 16 Standard Guide For Characterizing Environmental Aspects Of Manufacturing Processes*. [online] Astm.org. Available at: <https://www.astm.org/Standards/E3012.htm> [Accessed 13 September 2019].
5. Bernstein, W., Tamayo, C., Lechevalier, D. and Brundage, M., 2019. Incorporating unit manufacturing process models into life cycle assessment workflows. *Procedia CIRP*, 80, pp.364-369.
6. Bhat, C. and Mukherjee, A. (2019). Sensitivity of Life-Cycle Assessment Outcomes to Parameter Uncertainty: Implications for Material Procurement Decision-Making. Transportation Research Record.
7. Bhat, C. and Mukherjee, A., (2020). Life Cycle Thinking-Informed Approach to Support Pavement Design Decision Making. *Journal of Transportation Engineering, Part B: Pavements*, 146(4), p.04020067.
8. *Buy Clean California Act*; California, 2017; Vol. AB-262. Available at: https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act#@ViewBag.JumpTo
9. Carbonleadershipforum.org. 2019. *Concrete Product Category Rule | Carbon Leadership Forum*. [online] Available at: <http://www.carbonleadershipforum.org/2017/01/03/concrete-pcr/> [Accessed 6 April 2019].
10. Cashman, S., Meyer, D., Edelen, A., Ingwersen, W., Abraham, J., Barrett, W., Gonzalez, M., Randall, P., Ruiz-Mercado, G. and Smith, R. (2016). Mining Available Data from the United States Environmental Protection Agency to Support Rapid Life Cycle Inventory Modeling of Chemical Manufacturing. *Environmental Science & Technology*, 50(17), pp.9013-9025.
11. CEN (2012). Sustainability of Construction Works-Environmental Product Declarations-Core Rules for the Product Category of Construction Products. EN, 15804. The European Committee for Standardization (CEN: Comité Européen de Normalisation), Brussels, Belgium. | Available at: https://www.usgbc.org/resources/en-15804%E2%80%942012-sustainability-construction-works-environmental-product-declarations-core-ru
12. Chehovits, Jim, and Larry Galehouse. 2010. "Energy Usage and Greenhouse Gas Emissions of Pavement Preservation Processes for Asphalt Concrete Pavements". In *First International Conference on Pavement Preservation*. New Port Beach,

California. Available at: http://centralcoast.apwa.net/Content/Chapters/centralcoast.apwa.net/Documents/Energy%20Usage%20and%20Greenhouse%20Gas%20Emissions%20of%20Pavement%20Preservation%20Processes%20for%20Asphalt%20Concrete%20Pavements.pdf.

13. Ciroth, A. (2004). Uncertainties in life cycle assessment. *The International Journal of Life Cycle Assessment*, 9(3), pp.141-142.
14. Cooper, J., Noon, M. and Kahn, E., 2012. Parameterization in Life Cycle Assessment inventory data: review of current use and the representation of uncertainty. *The International Journal of Life Cycle Assessment*, 17(6), pp.689-695.
15. Cshub.mit.edu. 2019. *Pavement Vehicle Interaction (PVI) | Concrete Sustainability Hub*. [online] Available at: <http://cshub.mit.edu/pavements/pvi> [Accessed 6 April 2019].
16. Del Borghi, Adriana. 2012. "LCA And Communication: Environmental Product Declaration". *The International Journal of Life Cycle Assessment* 18 (2): 293-295. doi:10.1007/s11367-012-0513-9.
17. Denix.osd.mil. 2020. *ESOH In Acquisition - DENIX*. [online] Available at: <https://www.denix.osd.mil/esohacq/home/> [Accessed 17 March 2020].
18. Edelen, A. and Ingwersen, W. (2016). Guidance on Data Quality Assessment for Life Cycle Inventory Data. Life Cycle Assessment Research Center, National Risk Management Research Laboratory, *United States Environmental Protection Agency*.
19. Edelen, A., Ingwersen, W., Rodríguez, C., Alvarenga, R., de Almeida, A. and Wernet, G. (2017). Critical review of elementary flows in LCA data. *The International Journal of Life Cycle Assessment*, 23(6), pp.1261-1273.
20. Fhwa.dot.gov. 2019. *Sustainable Pavement Program - Sustainability - Pavements - Federal Highway Administration*. [online] Available at: <https://www.fhwa.dot.gov/pavement/sustainability/> [Accessed 5 April 2019].
21. Finnveden, G., Hauschild, M., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S. 2009. Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91(1), pp.1-21.
22. Fpl.fs.fed.us. 2020. *USDA Forest Service - Forest Products Laboratory*. [online] Available at: <https://www.fpl.fs.fed.us/> [Accessed 17 March 2020].
23. Gelowitz, M.D.C., and J.J. McArthur. 2017. "Comparison of Type III Environmental Product Declarations for Construction Products: Material Sourcing and Harmonization Evaluation". *Journal of Cleaner Production* 157: 125-133. doi: 10.1016/j.jclepro.2017.04.133.
24. GitHub. 2020. *Greendelta/Olca-Modules*. [online] Available at: <https://github.com/GreenDelta/olca-modules/tree/master/olca-core/src/main/java/org/openlca/core/model> [Accessed 23 August 2020].

25. Gregory, J., Noshadravan, A., Olivetti, E. and Kirchain, R. 2016. A Methodology for Robust Comparative Life Cycle Assessments Incorporating Uncertainty. *Environmental Science & Technology*, 50(12), pp.6397-6405.
26. Gregory, J., Noshadravan, A., Swei, O., Xu, X. and Kirchain, R., 2017, April. The importance of incorporating uncertainty into pavement life cycle cost and environmental impact analyses. In Proc., *Pavement Life-Cycle Assessment Symposium* (pp. 12-13).
27. Groen, E. and Heijungs, R. (2017). Ignoring correlation in uncertainty and sensitivity analysis in life cycle assessment: what is the risk? *Environmental Impact Assessment Review*, 62, pp.98-109.
28. Gruber, T. (1993). A translation approach to portable ontology specifications. Knowledge Acquisition, 5(2), pp.199-220.
29. Harvey, J., Lea, J., Kim, C., Coleri, E., Zaabar, I., Louhghalam, A., Chatti, K., Buscheck, J. and Butt, A., 2015. *Simulation Of Cumulative Annual Impact Of Pavement Structural Response On Vehicle Fuel Economy For California Test Sections*. [online] California Department of Transportation. Available at: <http://www.ucprc.ucdavis.edu/PDF/UCPRC-RR-2015-05.pdf> [Accessed 22 December 2019].
30. Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I., Saboori, A. and Kendall, A., 2016. *Pavement Life-Cycle Assessment Framework*. No. FHWA-HIF-16-014. Washington, D.C.: Federal Highway Administration. Available at: https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf
31. Heijungs, R., and S. Suh. The computational structure of life cycle assessment. Springer, Dordrecht, 2002.
32. Huijbregts, M., Gilijamse, W., Ragas, A. and Reijnders, L. (2003). Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling. *Environmental Science & Technology*, 37(11), pp.2600-2608.
33. Ingwersen, W. and Stevenson, M., 2012. Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. *Journal of Cleaner Production*, 24, pp.102-108.
34. IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
35. ISO 14025 (c): Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures, 2006, [online] Available at: https://www.iso.org/standard/38131.html (accessed Apr 6, 2019).
36. ISO 14040 (a): Environmental management — Life cycle assessment — Principles and framework, 2006, [online] Available at https://www.iso.org/standard/37456.html (accessed Apr 6, 2019).
37. ISO 14044 (b): Environmental management — Life cycle assessment — Requirements and guidelines, 2006, [online] Available at: https://www.iso.org/standard/38498.html [Accessed 6 Apr. 2019].

38. ISO 21930: Sustainability in building construction — Environmental declaration of building products, 2017. Available at: https://www.iso.org/standard/61694.html (accessed Apr 10, 2019)
39. Janowicz, K., Krisnadhi, A., Hu, Y., Suh, S., Weidema, B., Rivela, B., Tivander, J., Meyer, D., Berg-Cross, G., Hitzler, P., Ingwersen, W., Kuczenski, B., Vardeman, C., Ju, Y. and Cheatham, M., 2015. A Minimal Ontology Pattern for Life Cycle Assessment Data. In: *Workshop on Ontology and Semantic Web Patterns (6th edition)*.
40. Lcacommons.gov. 2019. *LCA Collaboration Server*. [online] Available at: <https://www.lcacommons.gov/lca-collaboration/> [Accessed 6 April 2019].
41. Li, H., 2012. *Evaluation Of Cool Pavement Strategies For Heat Island Mitigation*. Doctorate. University of California, Davis.
42. Lloyd, S., and R. Ries. 2008. Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches. *Journal of Industrial Ecology*, Vol. 11, No. 1, pp. 161-179.
43. Ma, Feng, Aimin Sha, Ruiyu Lin, Yue Huang, and Chao Wang. 2016. "Greenhouse Gas Emissions from Asphalt Pavement Construction: A Case Study in China". *International Journal of Environmental Research and Public Health* 13 (3): 351. doi:10.3390/ijerph13030351.
44. Mendoza Beltran, A., Prado, V., Font Vivanco, D., Henriksson, P.J., Guinée, J.B. and Heijungs, R., 2018. Quantified Uncertainties in Comparative Life Cycle Assessment: What Can Be Concluded? Environmental science & technology, 52(4), pp.2152-2161.
45. Morgan, M. and Henrion, M. (2007). Uncertainty. Cambridge: Cambridge Univ. Press.
46. Mukherjee, A., 2016. *Life Cycle Assessment Of Asphalt Mixtures In Support Of An Environmental Product Declaration*. [online] Lanham, MD: National Asphalt Pavement Association. Available at: <https://www.asphaltpavement.org/PDFs/EPD_Program/LCA_final.pdf> [Accessed 6 April 2019].
47. Mukherjee, A., Bhat, C. and Harvey, J., 2020. *Challenges In Meeting Data Needs For Use Of Environmental Product Declarations In Pavement Design And Construction: State Of Practice And Future Scope*. FHWA-HRT-20-022. [online] Federal Highway Administration. Available at: <https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/20022/> [Accessed 17 March 2020].
48. Mukherjee, A. and Cass, D., 2011. *Carbon Footprint For HMA and PCC Pavements*. [online] Michigan Department Of Transportation. Available at: <https://www.michigan.gov/documents/mdot/MDOT_Research__Report_RC-1553_363800_7.pdf> [Accessed 25 September 2020].
49. Netl.doe.gov. 2019. *National Energy Technology Laboratory*. [online] Available at: <https://www.netl.doe.gov/> [Accessed 8 April 2019].

50. NIST. 2020. *Metrics And Tools For Sustainable Buildings*. [online] Available at: <https://www.nist.gov/programs-projects/metrics-and-tools-sustainable-buildings> [Accessed 17 March 2020].
51. Noshadravan, A., Wildnauer, M., Gregory, J. and Kirchain, R. 2013. Comparative pavement life cycle assessment with parameter uncertainty. Transportation Research Part D: Transport and Environment, 25, pp.131-138.
52. Nrel.gov. 2019. *National Renewable Energy Laboratory (NREL) Home Page | NREL*. [online] Available at: <https://www.nrel.gov/> [Accessed 8 April 2019].
53. PADD Regions. Environmental Impact Administration (EIA) Available at: https://www.eia.gov/todayinenergy/detail.php?id=4890#:~:text=The%20Petroleum%20Administration%20for%20Defense,PADD%205%20the%20West%20Coast. Accessed Aug. 14, 2020.
54. Sen, S. and Roesler, J., 2016. Contextual heat island assessment for pavement preservation. *International Journal of Pavement Engineering*, 19(10), pp.865-873.
55. US EPA. 2019. *United States Environmental Protection Agency (USEPA)*. [online] Available at: https://www.epa.gov/ [Accessed 8 April 2019].
56. Usda.gov. 2019. *United States Department Of Agriculture (USDA)*. [online] Available at: <https://www.usda.gov/> [Accessed 8 April 2019].
57. Van Dam, T., Harvey, J., Muench, S., Smith, K., Snyder, M., Al-Qadi, I., Ozer, H., Meijer, J., Ram, P., Roesler, J. and Kendall, A., 2015. *Towards Sustainable Pavement Systems: A Reference Document*. FHWA-HIF-15-002. Washington, D.C.: Federal Highway Administration. Available at: https://www.fhwa.dot.gov/pavement/sustainability/hif15002/hif15002.pdf
58. Villa, F., Athanasiadis, I. and Rizzoli, A. (2009). Modelling with knowledge: A review of emerging semantic approaches to environmental modelling. *Environmental Modelling & Software*, 24(5), pp.577-587.
59. Wand, Y., Storey, V. and Weber, R., 1999. An ontological analysis of the relationship construct in conceptual modeling. *ACM Transactions on Database Systems*, 24(4), pp.494-528.
60. Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P. and Mathias, J. (2016). Using the Reliability Theory for Assessing the Decision Confidence Probability for Comparative Life Cycle Assessments. *Environmental Science & Technology*, 50(5), pp.2272-2280.
61. Yang, R.Y. (2014). Development of a Pavement Life Cycle Assessment Tool Utilizing Regional Data and Introducing an Asphalt Binder Model [MS Thesis]. University of Illinois, Urbana–Champaign, Urbana, Illinois. Accessed at: http://hdl.handle.net/2142/50651
62. Zaabar, I. and Chatti, K., 2010. Calibration of HDM-4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S. Conditions. *Transportation Research Record: Journal of the Transportation Research Board*, 2155(1), pp.105-116.
63. Zhang, Y., Luo, X., Buis, J. and Sutherland, J. (2015). LCA-oriented semantic representation for the product life cycle. *Journal of Cleaner Production*, 86, pp.146-162.

A Fundamental Construct of LCA

As an initial assumption for identifying entities (unit product system/processes) within pavement LCA system boundary, a product system is represented as a one-to-one mapping of flows to processes and represented using the graph-theoretic notation as follows:

$P \ = \{P1, P2, P3, P4, P5, P6\};$

$F \ = \{F1, F2, F3, F4, F5, F6\}$

$\pi \ (P, F) \ = \{(P1, P3), (P2, P3), (P3, P5), (P4, P5), (P5, P7), (P6, P7)\}$

where, P is a set of processes represented as nodes, and F is a set of flows represented as directed edges. The graph *π (P, F)* is a directed graph denoting the product system. Figure 33, illustrates graph for the product system *π (P, F)*

The flow, process and product system definitions are consistent with the model graph in OpenLCA and form the basis of this ontology.

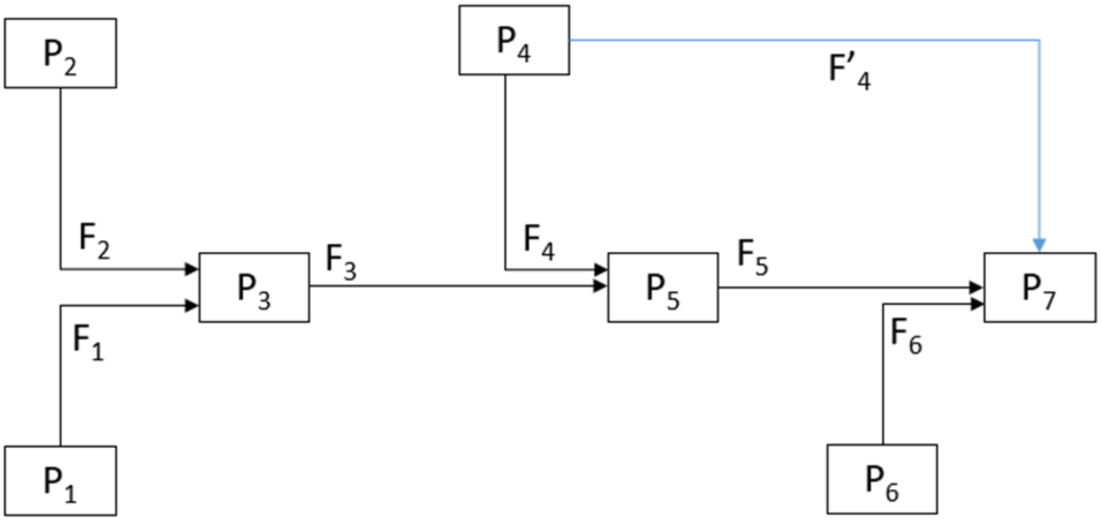


Figure A.1. 38. Definition of a Product System

B Background Data Quality Assessment Results

The use of LCIMs will shift the focus of the stakeholder to collect reliable foreground data and adapt to consistent background data present within LCIMs. However, it is of primary importance to determine the data quality of these background datasets prior to promoting them as the consistent data to be used within LCIMs. Hence, this section presents the data quality assessment of different background data categories relevant to pavement LCA available within the LCA Commons collaboration server. Public background datasets promise an advantage of accessibility and transparency but may compromise with the data quality due to inadequate specification of meta-data and absence of an internal or external review. This trade-off between accessibility and data quality may hinder the consistent use of public background datasets. Hence, this section identifies whether a background data category meets the desired data quality or not. The entities meeting the desired data quality are highlighted in green otherwise in red.

6.1.2 Electricity

Consumption-based electricity from the National Energy Technology Laboratory (NETL) (Source:https://www.netl.doe.gov/energy-analysis/details?id=bb9b0ec8-68b1-4406-8655-5bb4b095c7eb) has been chosen as the best available background dataset based on the discussions with the LCA Commons stakeholders. The results of data quality assessment for consumption-based electricity from NETL are as follows:

Reliability of the data
  a) Verified data based on measurements – score of 1
  b) Hosts but does not owns – score of 3
  c) No updates – score of 3
  d) Deterministic value provided – score of 3

Data Collection Methods
  a) Representative data from >80% of the relevant market, over an adequate period of time – score of 1
  b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 1

Time Period of Data
  a) Not Specified – score of 4
  b) N/A
  c) Less than 3 years old – score of 1

Geography of Data
  a) N/A
  b) State Level – score of 1

Technology of Data
  a) N/A
  b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for electricity. NETL's baseline electricity has recently been added to the LCA commons collaboration server resolving the compatibility issue with TRACI 2.1 impact assessment method from LCA Commons.

6.1.3 Natural Gas

Following technologies are relevant for the background data category "Natural Gas"

- Natural gas, combusted in industrial boiler (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/5b81b61c-4d10-3bed-9926-8a5f868f5174)
- Natural gas, combusted in industrial equipment (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/7b7babef-a97a-3510-88f2-ee70aa1fa03b)
- Operation of compressed natural gas equipment, industry average >19 kW and <56 kW(Source:https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/56a8fec2-9295-37b7-997d-03895b929db2)
- Operation of compressed natural gas equipment, industry average >56 kW and <560kW(Source:https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/6e687c52-4256-374e-b56f-6520c390a00e)
- Transportation by pipeline, natural gas powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/57cdac3b-a289-330e-8e55-6b7e2c6885fb)

Currently, natural gas from the United States Life Cycle Inventories' (USLCI's) National Renewable Energy Laboratory (NREL) and United States Environmental Protection Agency (USEPA) are available on the LCA Commons collaboration server. Hence, the data quality assessment was conducted only for these. The data quality assessment for the use of natural gas in industrial boiler, industrial equipment and transportation hosted by USLCI's NREL are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for natural gas used in industrial boiler, industrial equipment and transportation. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data. These limitations may be overcome with the availability of life cycle inventory data for natural gas used in industrial boiler, industrial equipment and transportation from Argonne National Laboratory (based on GREET model) and NETL on the LCA Commons collaboration server in the future. The data quality assessment for the use of natural gas in heavy construction equipment hosted by USEPA are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) Less frequent updates – score of 2
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Less than 6 years old – score of 2

Geography of Data
a) N/A
b) Continental Level – score of 3

Technology of Data
a) N/A
b) Specified – score of 1

Process Review
a) The process has documented review by an internal reviewer – score of 4

Process Completeness
a) >80% of determined flows within the process have been evaluated and given a value – score of 1
b) Including meta-data on life cycle inventory review, improving the regional granularity of data can aid towards achieving the desired data quality for natural gas used in heavy construction equipment. In addition, there is a need for the life cycle inventory data to be reviewed by a minimum of two third-party reviewers.

6.1.4 Diesel

Following technologies are relevant for the background data category "Diesel"

- Diesel, combusted in industrial boiler (Source: https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/53804132-4bd6-3b18-bfbd-14ac762431ef)
- Diesel, combusted in industrial equipment (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/d6ad7035-5498-3237-8abd-50e93b1eef89)
- Operation of diesel equipment, industry average <19kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/b66a6f70-3c42-3383-a5c8-181db03c238e)
- Operation of diesel equipment, industry average >19 kW and <56 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/550cd813-8af9-3947-8639-82b5efb52227)
- Operation of diesel equipment, industry average >56 kW and <560 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/8df6b552-259c-358c-b6eb-86c3f8c2e339)

- Operation of diesel equipment, industry average >560 kW and <900 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/930dce69-1a9d-34c5-81d3-7347213a3938)
- Operation of diesel equipment, industry average >900 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/fdc1b60d-9862-33dd-8296-b9d45bdf58a4)
- Transportation by barge, diesel powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/c2300fc3-5496-3d12-9135-67dc0ef740c9)
- Transportation by combination truck, diesel powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/34156f3c-28ef-33db-9ad0-6293a2aa0d52)
- Transportation by ocean freighter, diesel powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/da0f5501-f4ab-32d1-80b7-b70d143608f6)
- Transportation by train, diesel powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/7de9c230-fd0f-3478-be87-f80181132faa)
- Transport, refuse truck, diesel powered (Source: https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/16d56c2f-7a14-33c1-863d-baecbc1b5170)

Currently, diesel from the USLCI's NREL and USEPA are available on the LCA Commons collaboration server. Hence, the data quality assessment was conducted only for these. The data quality assessment for the use of diesel in industrial boiler, industrial equipment, transportation and end-of-life processes hosted by USLCI's NREL are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4

b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data
a) N/A
b) Continental Level – score of 3

Technology of Data
a) N/A
b) Specified – score of 1

Process Review
a) The process has no documented review – score of 5

Process Completeness
a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for diesel used in industrial boiler, industrial equipment and transportation. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data. These limitations may be overcome with the availability of life cycle inventory data for diesel used in industrial boiler, industrial equipment and transportation from Argonne National Laboratory (based on GREET model) and NETL on the LCA Commons collaboration server in the future. The data quality assessment for the use of diesel in heavy construction equipment hosted by USEPA are as follows:

Reliability of the data
a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) Less frequent updates – score of 2
d) Deterministic value provided – score of 3

Data Collection Methods
a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data
a) Not Specified – score of 4
b) N/A
c) Less than 6 years old – score of 2

Geography of Data
a) N/A

b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has documented review by an internal reviewer – score of 4

Process Completeness

a) >80% of determined flows within the process have been evaluated and given a value – score of 1

Including meta-data on life cycle inventory review, improving the regional granularity of data can aid towards achieving the desired data quality for diesel used in heavy construction equipment. In addition, there is a need for the life cycle inventory data to be reviewed by a minimum of two third-party reviewers.

6.1.5 Gasoline

Following technologies are relevant for the entity "Gasoline"

- Gasoline, combusted in industrial equipment (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/d3e13675-1455-375f-a557-bb8234de75ff)
- Transportation by combination truck, gasoline powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/463d05c9-8c19-3030-8b9f-380c098f5116)
- Operation of gasoline equipment, 2-stroke, industry average <19 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/b44fcc11-cd9e-3cf7-9a5a-db38eacb1d6b)
- Operation of gasoline equipment, 4-stroke, industry average <19 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/ea4e8e6d-878a-36ba-97d4-6d13b13b2ef7)
- Operation of gasoline equipment, industry average <19 kW and >56 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/6be00cb2-47b9-3b57-9944-15fbc57f69af)
- Operation of gasoline equipment, industry average >56 kW and <560 kW (Source: https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/769eae14-1bfc-39e7-90f7-5d059b8d197f)

- Transport, refuse truck, gasoline powered (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/53ffa5d2-4622-30c8-8135-e1eac2d0b268)

Currently, gasoline from the USLCI's NREL and USEPA are available on the LCA Commons collaboration server. Hence, the data quality assessment was conducted only for these. The data quality assessment for the use of gasoline in industrial boiler, industrial equipment, transportation, and end-of-life processes hosted by USLCI's NREL are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for gasoline used in industrial boiler, industrial equipment and transportation. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data. These limitations may be overcome with the availability of life cycle inventory data for gasoline used in industrial boiler, industrial equipment and transportation from Argonne National Laboratory (based on GREET model) and NETL on the LCA Commons collaboration server in the future. The data quality assessment for the use of gasoline in heavy construction equipment hosted by USEPA are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) Less frequent updates – score of 2
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Less than 6 years old – score of 2

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has documented review by an internal reviewer – score of 4

Process Completeness

a) >80% of determined flows within the process have been evaluated and given a value – score of 1

Including meta-data on life cycle inventory review, improving the regional granularity of data can aid towards achieving the desired data quality for gasoline used in heavy construction equipment. In addition, there is a need for the life cycle inventory data to be reviewed by a minimum of two third-party reviewers.

6.1.6 Liquefied Petroleum Gas

Following technologies are relevant for the entity “Liquefied Petroleum Gas”

- Liquefied petroleum gas, combusted in industrial boiler (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/4eec7a31-b920-3f91-b7c3-924f2aa92ecc)

- Operation of liquefied petroleum gas equipment, industry average >19 kW and <56 kW(Source:https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/10499ec7-eb9b-3e1a-80ac-3dd3dcfa3830)
- Operation of liquefied petroleum gas equipment, industry average >56 kW and <560kW(Source:https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/Heavy_equipment_operation/dataset/PROCESS/12ecfd99-a5bd-32bd-8d38-99307d8ef37a)

Currently, liquefied petroleum gas from the USLCI's NREL and USEPA are available on the LCA Commons collaboration server. Hence, the data quality assessment was conducted only for these. The data quality assessment for the use of liquefied petroleum gas in industrial boiler, industrial equipment, transportation and end-of-life processes hosted by USLCI's NREL are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for liquefied petroleum gas used in industrial boiler, industrial equipment and transportation. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data. These limitations may be overcome with the availability of life cycle inventory data for liquefied petroleum gas used in industrial boiler, industrial equipment and transportation from Argonne National Laboratory (based on GREET model) and NETL on the LCA Commons collaboration server in the future.

6.1.7 Residual Fuel Oil

Following technologies are relevant for the entity "Residual Fuel Oil"

- Residual fuel oil, combusted in industrial boiler (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/9d9b6815-9349-30af-869b-57362428c42e)

Currently, residual fuel oil from the USLCI's NREL is available on the LCA Commons collaboration server. Hence, the data quality assessment was conducted only for these. The data quality assessment for the use of residual fuel oil in industrial boiler, industrial equipment, transportation and end-of-life processes hosted by USLCI's NREL are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for residual fuel oil used in industrial boiler, industrial equipment and transportation. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data. These limitations may be overcome with the availability of life cycle inventory data for residual fuel oil used in industrial boiler, industrial equipment and transportation from Argonne National Laboratory (based on GREET model) and NETL on the LCA Commons collaboration server in the future.

6.1.8 Coal

Following technologies are relevant for the entity "Coal"

- Anthracite coal, combusted in industrial boiler (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/27e8fce4-a5c1-37af-84b9-763582a5ca3e)
- Bituminous coal, combusted in industrial boiler (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/26465530-69ff-3c68-834f-c67ccb6ee1b2)
- Lignite coal, combusted in industrial boiler (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/1b0f75b8-e749-3eb2-8727-de6a22f60646)

Currently, Coal from the USLCI's NREL is available on the LCA Commons collaboration server. Hence, the data quality assessment was conducted only for these. The data quality assessment for the use of anthracite coal, bituminous coal and lignite coal in industrial boiler hosted by USLCI's NREL are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for coal used in industrial boiler, industrial equipment and transportation. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data. These limitations may be overcome with the availability of life cycle inventory data for coal used in industrial boiler, industrial equipment and transportation from Argonne National Laboratory (based on GREET model) and NETL on the LCA Commons collaboration server in the future.

6.1.9 Asphalt Binder

Following technologies are relevant for the entity "Asphalt Binder"

- Asphalt binder, no additives, consumption mix, at terminal, from crude oil (Source: http://www.asphaltinstitute.org/engineering/lca-study-on-asphalt-binders/)
- Asphalt binder, 0.5% polyphosphoric acid (PPA), consumption mix, at terminal, from crude oil (Source: http://www.asphaltinstitute.org/engineering/lca-study-on-asphalt-binders/)
- Asphalt binder, 3.5% styrene-butadiene-styrene (SBS), consumption mix, at terminal, from crude oil (Source: http://www.asphaltinstitute.org/engineering/lca-study-on-asphalt-binders/)
- Asphalt binder, 8% ground rubber tire (GRT), consumption mix, at terminal, from crude oil (Source: http://www.asphaltinstitute.org/engineering/lca-study-on-asphalt-binders/)
- Liquid Asphalt Binder, in refinery (Source: Mukherjee, 2016)
- Liquid Asphalt Binder, with polymer (Source: Mukherjee, 2016)

Currently, asphalt binder from the Asphalt Institute and National Asphalt Pavement Association (NAPA) are available in the OpenLCA compatible format. Hence, the data quality assessment was conducted only for these. The data quality assessment for asphalt binder from Asphalt Institute are as follows:

Reliability of the data

a) Verified data based on measurements – score of 1
b) Hosts but does not owns– score of 3
c) Less frequent updates – score of 2
d) Deterministic value provided – score of 3

Data Collection Methods

a) Representative data from 40-59% of the relevant market, over an adequate period – score of 3
b) Life-cycle inventory data is not compatible with TRACI 2.1 impact assessment method from LCA Commons– score of 4

Time Period of Data

a) All three (fall, spring and summer) seasons are covered – score of 1
b) N/A
c) Less than 6 years old – score of 2

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) Documented reviews by a minimum of two types of reviewers, with one being a third party– score of 2

Process Completeness

a) >80% of determined flows have been evaluated and given a value– score of 1

Asphalt institute's LCA team worked with NREL to make their life cycle inventory compatible with the LCA Commons TRACI 2.1 impact assessment method and the dataset has recently been added to the LCA commons collaboration server.

The data quality assessment for asphalt binder from USLCI are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3

d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

Including meta-data on life cycle inventory review, time period for updating the data can aid towards achieving the desired data quality for asphalt binder. In addition, the life cycle inventory needs to be updated or at least the reason for using more than 15 year old data should be stated in the meta-data. There is also a need to improve the regional granularity of life cycle inventory data.

6.1.10 End of Life Processes

These are some initial end-of-life processes available from LCA Commons collaboration server.

- Aluminum recovery, transport to plant (Source: https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/d20197e1-967f-35cb-95c1-0dbde806c367)
- Mixed recyclables, at collection, commercial (Source: https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/d4647fd6-57bf-3557-b3fe-be8dbc0eb6da)
- Mixed recyclables, sorted at MRF (Source: https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/b5c35450-2b29-3f72-b6bf-1836a9d55100)

- Mixed recyclables to MRF (Source: https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/e93ae1c1-8454-328d-aef7-3698311ae06a)

The data quality assessment for end-of-life processes from USEPA are as follows:

Reliability of the data

a) Undocumented Estimate – score of 5
b) Hosts but does not owns – score of 3
c) No updates – score of 3
d) Deterministic value provided – score of 3

Data Collection Methods

a) Unknown OR data from a small number of sites and from shorter periods – score of 5
b) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – score of 1

Time Period of Data

a) Not Specified – score of 4
b) N/A
c) Age of data unknown or more than 15 years – score of 5

Geography of Data

a) N/A
b) Continental Level – score of 3

Technology of Data

a) N/A
b) Specified – score of 1

Process Review

a) The process has no documented review – score of 5

Process Completeness

a) Process completeness not scored – score of 5

At this time, the collection of background data is limited to the technologies relevant from LCA Commons collaboration server. However, the background data quality assessment approach discussed in this dissertation may be applied to the background data to be collected from the pavement industry (e.g., for other surface materials, additives and admixtures) as well.

C Copyright documentation

The image used in Figure 10 has been taken from the following open source link : https://www.eia.gov/todayinenergy/detail.php?id=4890