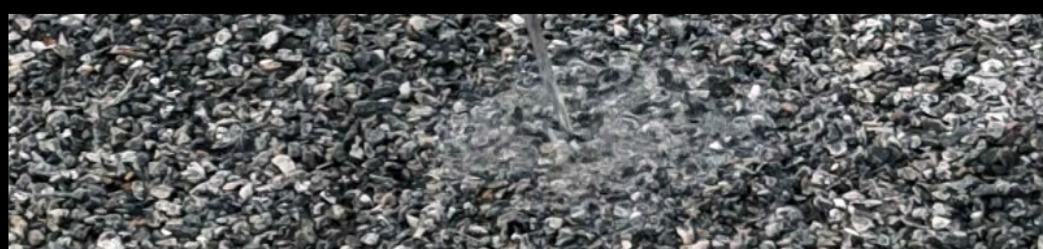
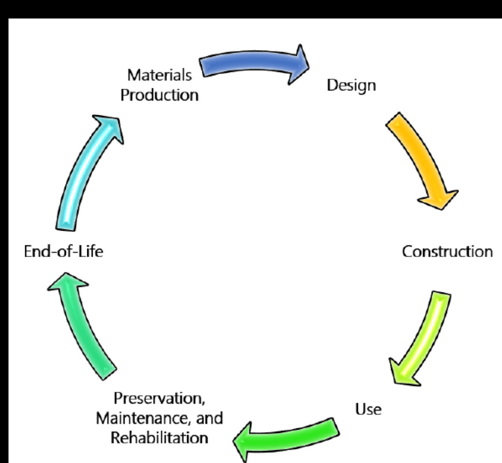
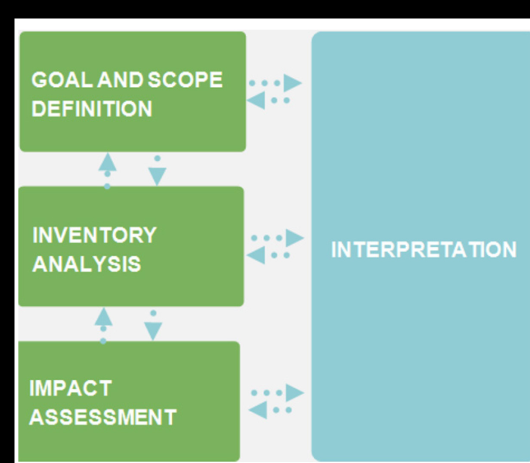
U.S. Department
of Transportation
Federal Highway
Administration

Pavement Life Cycle Assessment Framework

FHWA-HIF-16-014







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16. Abstract

Awareness of the importance of environmental protection, and the possible impacts associated with the production, use, and retirement of products, has generated considerable interest in the use of assessment methods to better understand and address those impacts. Life-cycle assessment (LCA) is one of the techniques developed for this purpose. LCA is a structured evaluation methodology that quantifies environmental impacts over the full life cycle of a product or system, including impacts that occur throughout the supply chain. LCA provides a comprehensive approach for evaluating the total environmental burden of a product by examining all the inputs and outputs over the life cycle, from raw material production to the end-of-life (EOL). For pavements, this cycle includes the material production, design, construction, use, maintenance and rehabilitation (M&R), and EOL stages.

LCA has a commonly accepted standard method (published by the International Organization for Standardization [ISO]), however, specifics within this method vary greatly from one application to another. Additionally, there are no widely accepted standards that focus on pavement-LCA. This pavement LCA framework document is an important first step in the implementation and adoption of LCA principles in the pavement community within the U.S. A framework for performing an LCA specific to pavement systems along with guidance on the overall approach, methodology, system boundaries, and current knowledge gaps are presented in this document.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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ACRONYMS

AC	Asphalt Concrete
ADP	Acidification Potential
CARB	California Air Resources Board
CDW	Construction Demolition Waste
CEM	Continuous Emission Measurements
CH_4	Methane
CLF	Carbon Leadership Forum
CML	Center for Environmental Studies at the University of Leiden, the Netherlands
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CRS	Condition Rating System
CTUs	Comparative Toxicity Units
CY	Cubic Yard
DARS	Data Attribute Rating System
DOT	Department of Transportation
EIA	Energy Information Administration
EIO	Economic Input Output
EIO-LCA	Economic Input-Output Life-Cycle Assessment
EOL	End-of-Life
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infrared Spectroscopy
FWD	Falling Weight Deflectometer
GHG	Greenhouse Gas
GWP	Global Warming Potential
H+	Hydrogen Ion
HCC	Hydraulic Cement Concrete
HHV	Higher Heating Value
HMA	Hot-Mix Asphalt
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LCSA	Triple-Bottom Line Sustainability Assessment
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
M&R	Maintenance and Rehabilitation
ME	Mechanistic-Empirical
MOVES	Motor Vehicle Emission Simulator
MPD	Mean Profile Depth
NGOs	Nongovernmental Organizations
N_2O	Nitrous Oxide

NO_x	Nitrogen Oxides
O_3	Tropospheric Ozone
ODP	Ozone Depletion Potential
PADD	Petroleum Administration Defense Districts
PAH	Polycyclic Aromatic Hydrocarbon
PCA	Portland Cement Association
PCE	Passenger Car Equivalent
PCI	Pavement Condition Index
PED	Primary Energy Demand
PCR	Product Category Rule
POCP	Photochemical Ozone Creation Potential
PPA	Polyphosphoric Acid
QA/QC	Quality Assurance/Quality Control
RAP	Recycled Asphalt Pavement
RCA	Recycled Concrete Aggregate
RF	Radiative Forcing
RWD	Rolling Weight Deflectometer
SCM	Supplementary Cementitious Material
S-LCA	Social LCA
SO_2	Sulfur Dioxide
SY	Square Yard
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UCMs	Urban Canopy Models
UHI	Urban Heat Island
VOCs	Volatile Organic Compounds
W/m^2	Watts Per Meter Square
WARM	WAste Reduction Model
WCED	World Commission on Environment and Development
WTB	Well to Blending
WTR	Well to Refinery

CHAPTER 1. INTRODUCTION

1.0 Background

An increasing number of agencies, companies, organizations, institutes, and governing bodies are embracing principles of sustainability in managing their activities and conducting business. These principles focus on the overarching goal of proactively bringing key environmental, social, and economic factors into the decision-making process. Sustainability considerations are not new, as they were often considered indirectly or informally in the past. However, recent years have seen increased efforts to quantify sustainability effects as they pertain to pavements, systematically incorporating them into decision making in a more organized fashion (Van Dam et al. 2015).

1.0.1 Sustainability Defined

Most definitions of sustainability begin with that issued by the World Commission on Environment and Development (WCED), often referred to as the *Brundtland Commission Report* (WCED 1987):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

This definition is focused on the concept of “needs” and the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs. In a shorter version of this, sustainability is often described as being made up of the three components of environmental, social, and economic needs, collectively referred to as the “triple-bottom line.”

For many years, the economic component has been the dominant decision factor, but more recent years have seen the growing emergence of both the environmental and social components (even though there are some current limitations associated with their measurement and assessment). A focus on sustainability can then be interpreted in such a way that all triple-bottom line components are considered important, but the relative importance of these factors (and how each is considered) are case sensitive, very much driven by the goals, demands, characteristics, and constraints of a given project.

“Sustainability,” in the context of pavements, refers to system characteristics that encompass a pavement’s ability to (Van Dam et al. 2015):

- Achieve the engineering goals for which it were constructed.
- Preserve and (ideally) restore surrounding ecosystem.
- Use financial, human, and environmental resources economically.
- Meet basic human needs such as health, safety, equity, employment, comfort, and happiness.

1.1 Measuring Sustainability

The “measurement” of sustainability is the first step in being able to establish benchmarks and assess progress. There are a number of different measurement tools and methods available for assessing and defining pavement sustainability, all of which have strengths and weaknesses and may be used individually or in combination. The four most relevant tools or methods for quantifying aspects of sustainability are described below:

- **Performance Assessment**. Performance assessment involves evaluating pavement performance in relation to the pavement's intended function. Performance is most often addressed in relation to that of the current standard practice. For instance, if the current standard asphalt pavement surfacing is expected to last 15 years, the value of an alternative surfacing (e.g., open-graded friction course, stone matrix asphalt, or rubberized asphalt concrete) is based on the projected service life of the considered alternative relative to the 15-year service life of the standard surface. The most common sentiment is that alternatives must perform equally to or better than the current standard practice (although this may be a narrow view because it does not consider other possible added benefits). Performance may also be addressed in terms of specific physical attributes (e.g., pavement structural capacity, material attributes, and condition or distress measures) and the behavior mechanisms that link these attributes to expected performance.
- **Life-Cycle Cost Analysis (LCCA)**. LCCA is an analysis technique that uses economic analysis to evaluate the total cost of an investment option in constant dollars over an analysis period. As such, it is principally used to address the economic component of sustainability. One underlying assumption of LCCA is that the benefits of considered alternatives are equal, so only costs (or differential costs) must be considered. LCCA does not directly address societal or environmental issues (e.g., clean air and water, habitat impacts, establishment of livable community conditions) unless such issues can be monetized and treated purely as costs. Caution should be exercised when environmental issues are monetized and this is often discouraged due to: (a) challenges associated with determining a monetary value and (b) potential for double counting when both life-cycle assessment (LCA) and LCCA are performed.

  The Federal Highway Administration (FHWA) encourages the use of LCCA as a decision-support tool, as is stated in their 1981 Pavement Type Selection Policy Statement (Federal Register 1981), and has provided guidance in an Interim Technical Bulletin (Walls and Smith 1998). The most prevalent LCCA software tool for pavements is the FHWA's RealCost program (FHWA 2011).
- **Sustainability Rating Systems**. A sustainability rating system is essentially a list of practices or features that impact sustainability, coupled with a common unit of measurement (usually a point system) that quantifies the relative impacts. In this way, the diverse impacts of various practices and features (e.g., pollutant loading in storm water runoff, changes in pavement design life, tons of recycled materials used, energy consumed and saved, pedestrian accessibility, ecosystem connectivity, and even the value of art) can all be compared using a common unit (rating points).

  In its simplest form, a rating system may count the implementation of every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used. In more complex forms, rating systems weight best practices (usually in relation to their impact on a selected definition of sustainability or a selected set of priorities), which can assist in choosing the most impactful best practices to use given a limited scope or budget. Many national and international pavement sustainability rating systems are currently available (e.g., INVEST, Greenroads, and Envision).

- **Life-Cycle Assessment (LCA)**. LCA is a technique that can be used for analyzing and quantifying the environmental impacts of a product, system, or process. LCA provides a comprehensive approach to evaluating the total environmental burden of a product or process by examining all of the inputs and outputs over the life cycle, from raw material production to end of life. This systematic approach identifies where the most relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs. The processes and rules for conducting an LCA are generally defined by the International Organization for Standardization (ISO) in its 14040 family of standards (ISO 2006). These standards are quite broad; thus, more precise guidance is needed for their application to a specific material or process. Such guidance is usually developed by the relevant industries and other stakeholders.

  LCA is a field of science that is still evolving, yet it has demonstrated real-world value over the last two decades by helping manufacturers, companies, governments and other groups identify what is environmentally important to them and then to define needed actions to improve their environmental impacts. An increasing number of industries are creating LCA-based Environmental Product Declarations (EPD) to attest to the environmental performance of products that can be used in pavement LCA, which creates the need for harmonization.

  The earliest application of LCA to pavements was in the 1990s. LCA is now widely used in Europe in the construction industry and some countries (e.g., France and the Netherlands) include LCA in green construction regulations that govern pavements and other structures. Only recently (within the last 5 years) has LCA begun to be considered as a decision support tool in North America.

Each of the four tools described above offers certain unique benefits. For example, performance assessment is a longstanding method of evaluation, essentially measuring engineering performance and often comparing it to a commonly accepted standard. The use of LCCA to assess cost impacts for pavements is well established, and is a subset of a larger group of methods for assessing the macroeconomic impacts of spending on transportation in general. Rating systems are easily understood and are emerging worldwide and several have been implemented by various groups. LCAs are an emerging technology with a well-established baseline process (i.e., the ISO 14040 series of standards), but their use for pavements still requires considerable work to define specific rules and common practices, and to establish how LCA results should best be used to measure and assess environmental (and perhaps social) impacts for pavement systems.

One key to making good pavement-related decisions is to have an understanding of where environmental impacts are created in the life cycle of pavements, as well as how and to what extent various sustainability strategies actually reduce those environmental impacts. It is also important to be able to identify potential unintended consequences that can result in increased environmental impacts. Best practices in pavement engineering should be adopted to ensure that the materials, design practices, construction and maintenance procedures used are appropriate for the site-specific conditions. This document focuses on pavement LCA as a tool for assisting in pavement-related decision making by quantifying environmental impacts over the full pavement life cycle.

1.2 Pavement Life Cycle

Reference has been made to the pavement life cycle, which is a useful means of describing the stages that a pavement goes through from its initial design development to the end of its useful life. An LCA looks at the environmental impacts over that entire pavement life cycle, which is illustrated in figure 1-1.

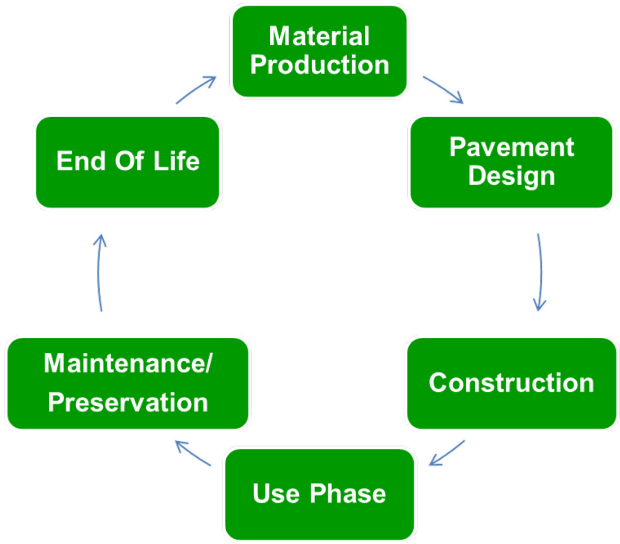

Figure 1-1. Pavement life-cycle stages.

- **Material Production**. Material production includes all processes used in the acquisition (e.g., mining and crude oil extraction) and processing (e.g., refining, manufacturing and mixing) of pavement materials.
- **Design**. The design stage refers to the process of identifying the structural and functional requirements of a pavement for given site conditions (i.e., subgrade, climate, traffic, existing pavement structure, etc.), as well as the determination of the pavement structural composition and accompanying materials.
- **Construction**. The construction stage includes all processes and equipment associated with the construction of the initial pavement.
- **Use Phase**. The use phase refers to the period during which the pavement is in service and is interacting with vehicles and the environment.
- **Maintenance/Preservation**. These are activities applied at various times throughout the life of the pavement to maintain its overall serviceability.
- **End of Life**. The end-of-life stage refers to the final disposition and subsequent reuse, processing, or recycling of the pavement after it has reached the end of its useful life.

Additional details concerning the pavement life cycle, including factors and considerations associated with each stage, are described in chapter 2.

1.3 Common Uses of Pavement LCA

At the present time, the use of LCA in the pavement community is growing but is still limited and only a few agencies are working to apply LCA in a consistent way. That said, the most common current uses of pavement LCA in North America are for the following purposes:

- Selection of a material or pavement structural design in conjunction with LCCA.
- Evaluation of the impacts of potential changes in a policy or specification.
- Development of LCA tools for screening or detailed LCA for the scoping or design of a project.
- Evaluation of scenarios for network-level decisions and strategies for preservation, maintenance and rehabilitation.
- Development of material EPDs for pavement applications.

It is important to note that each use may require a different type of LCA approach, which is defined in the first phase of the LCA (goal and scope definition). The intended use should always be kept in mind when drawing conclusions during the final phase of LCA (interpretation). It also means that the relevancy of (and the level of detail required by) some sections of this document depend on what is to be accomplished, as each phase of the LCA process and the steps within each phase depend on the intended purpose of the LCA study.

The "complexity" of an LCA study will vary with the number, nature, and the required precision of elements that are included in the study, as well as with the level of effort required for data gathering and impact calculations. LCA study complexity can be broadly categorized as follows:

- **Benchmarking studies, which are intended to provide baseline results for the comparison of alternative decisions and are mostly based on the life-cycle inventory (LCI).** These studies are often limited to:
  - Goal and system definition.
  - Determination of the flows of materials and resources into the system and the products, wastes and pollutants out of the system.
  - Quantitative comparisons of those results.

  These types of studies can be limited to focus only on the differences between alternatives, disregarding the parts that are similar. This results in a limited goal and scope that can significantly reduce the overall levels of complexity and effort. The limited goal and scope will also reduce the effort required for the interpretation phases. Usually, these types of studies do not include impact assessment and only include inventory data such as energy, emissions, and waste. Further, they are not considered a full LCA, but instead begin the process of applying LCA methodologies to decision making.
- **LCA studies with only a few impact indicators or that only consider selected stages of the full life cycle**. These studies usually cover all of phases of an LCA and include the development of life-cycle inventories (LCI) and life-cycle impact assessment (LCIA). Current pavement LCA studies that mostly look at energy flows and greenhouse gas (GHG) emissions tend to fall into this category. The interpretation phase may include less detail than is called for in a more comprehensive LCA; however, it will typically

include sensitivity assessment and complete documentation of its limitations for transparency reasons.

- **LCA studies that include LCI and LCIA for a larger set of impact indicators and interpretation, and consider the complete pavement life cycle.** These types of studies can be referred to as full LCA studies, and it is expected that an increasing number of full pavement LCA studies will be developed in North America in the coming years. One driver to this expected increase is that a full LCA is generally required for EPDs, as called for in the Product Category Rule (PCR) documents, except that the life-cycle stages only go from the cradle to the gate of the producer's plant.

The different levels of complexity are also considered in the detailed descriptions of LCA processes in the remaining chapters with the guidance and commentary provided in this document assisting agencies in conducting the types of studies discussed above.

1.4 Document Overview

This document is intended to provide LCA guidance but is not intended to set LCA standards. It provides a general framework for conducting LCA studies on pavement materials, projects and systems, describing the current status of the LCA methodology and its application to pavements. Importantly, this document provides guidance for agencies, but also allows for the description of viable alternatives (and their pros and cons) where they exist, as well as the documentation of current practices and experiences.

1.4.1 Chapter Listing

This document consists of eight chapters (including this introductory chapter), with the bulk of the document organized to follow the step-by-step process for conducting a pavement LCA as outlined by the ISO 14040 standards. A description of the primary chapters in this document is provided below:

- **Chapter 2: A Primer on Pavement Life-Cycle Assessment**. This chapter presents a high-level overview of LCA principles and the key elements of LCA; it also provides an introductory overview of how LCA may be applied to pavements.
- **Chapter 3: Goal and Scope Definition**. The first phase of any LCA study is the goal and scope definition. In this phase, the goal for the LCA is established and clearly stated, which helps define how the study is conducted, determines the precise product or process to be analyzed, and sets boundary conditions. A well-defined study goal and scope is needed to clearly identify choices and assumptions with respect to the most important elements of the LCA, such as the functional unit, analysis period, system boundaries, life-cycle inventory, and impact categories.
- **Chapter 4: Life-Cycle Inventory Analysis**. The second phase of an LCA is the life-cycle inventory analysis, in which the data necessary to satisfy the goal and scope are collected and processed and the types of input and output data that are expected (e.g., the energy and materials that are consumed and the emissions and waste that are created) are described. This chapter includes approaches and suggestions concerning the different aspects of the LCI phase, covering the unit processes, cut-off criteria, data types and sources, data-quality requirements, and procedures to address missing data. It is written with the practicalities of the actual inventory process in mind and uses a number of illustrations to show how the inventory can be organized and executed.

- **Chapter 5: Impact Assessment**. LCIA translates the results of a LCI into measures of human or environmental impacts or damages. The translation of LCI results into impacts is conducted using a scientific basis that considers the impact chain (or cause-and-effect chain) of an environmental flow on humans, the natural environment, or the depletion of natural resources. This chapter outlines the steps that are included in the impact assessment, including:
  - Selection of impact categories, category indicators and characterization models.
  - Assignment of LCI results to the selected impact categories (classification).
  - Calculation of category indicator results (characterization).
  - Normalization.
  - Grouping.
  - Weighting.

  It includes an overview of the most widely used impact assessment methods and impact categories (e.g., global warming, fresh water use, human toxicity, resource use, etc.).
- **Chapter 6: Interpretation**. The interpretation phase of the LCA is where the results are presented for the functional unit, the major contributions are identified and explained in terms of where the impacts are incurred, the uncertainty is described for the data and for the scenarios used, and sensitivity analyses are conducted over possible variations that can be justified for the most important methodological assumptions. This chapter includes a discussion of the following:
  - Identification of major issues based on findings of the LCI and LCIA phases.
  - Evaluation procedure to ensure completeness.
  - Sensitivity and consistency check.
  - Conclusions.
  - Appropriateness of the definitions of the system functions, the functional unit, and the system.
  - Limitations identified by the data-quality assessment and the sensitivity analysis.
  - Recommendations.
- **Chapter 7: Critical Review**. Critical review is one of the core elements of LCA and serves to verify whether an LCA has met the requirements for methodology, data, interpretation and reporting. This chapter covers the need and guidelines for three situations where critical review is important:
  - Critical review of an LCA study.
  - Review during the development of a Product Category Rule document.
  - Review of a proposed Environmental Product Declaration.

  This chapter includes guidance and information on the types of review and on the review process itself.
- **Chapter 8: Reporting**. A well-written LCA report starts with a systematic and comprehensive summary of the outcome of the LCA study. It also includes a transparently presented overview of the data, methods, assumptions, results and

limitations in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. This chapter discusses the background information and general motivation for the study, and provides guidance for reporting and interpreting the relevant results and conclusions from the different life-cycle stages. When relevant, it also includes reporting on the results from the critical review process, including additional requirements for comparative LCA studies to be disclosed to the public. LCA reporting that follows the guidelines in this chapter should result in a well-documented study.

Chapters 3 through 8 of the document are all structured similarly, incorporating the following sections:

- An introduction that includes an overview of the most important steps (presented in a flow diagram, where possible), the critical terminology, and the relation of the topic to the most important uses of LCA for agencies.
- A section with guidance on the application of the topic that follows the ISO steps from the flow diagram. There are three possible types of information within each chapter application guidance section:
  - Where possible, the guidance provided includes general consensus best practices (i.e., "should" recommendations). Agencies can use these best practices as generally agreed upon starting points.
  - If there is no general consensus, an overview of acceptable approaches is presented and the user can select the best approach for the LCA application at hand (i.e., "can" options).
  - There are also topics that are still in the early stages of research and for which no clear-cut guidance on best practice exists. In these cases, it is clearly noted that additional research is needed or is currently underway and that no clear consensus currently exists.
- A section with discussion and background for the guidance (chapters 3, 4, 6, and 8 only). The content of this section varies and depends on the topic for which guidance is being provided. Typical information discussed under this section includes: scientific background and description of the rationale to be adopted, a description of different options that can be considered and, in some cases, examples of how to apply the guidance.

In addition, appendices are included in support of this document. Appendix A provides an example checklist for reporting the scope of an LCA, appendix B presents a glossary of terms used throughout the document, and appendix C provides a list of suggested reading material relevant to practical implementation of LCA principles.

1.4.2 Target Audience

The primary audience for this document comprises LCA tool developers, state Department of Transportation (DOT) practitioners, and groups or organizations working with them to investigate LCA processes or to develop or evaluate LCA tools. Other audience members include PCR developers, EPD producers, and consultants commissioned by DOTs to perform LCA. Other key stakeholders in the pavement community expected to benefit from the information contained in this document include local roadway agencies, industry (i.e., suppliers, producers, contractors and consultants), academia, and various public interest groups.

1.4.3 Document Perspective

The application of LCA to pavements is evolving and it is expected that this document will be updated and improved as the methodology for conducting pavement LCAs continues to develop over the coming years. This document is intended to provide guidance only, and should not be considered to be a standard, requirement or specification.

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CHAPTER 2. A PRIMER ON PAVEMENT LIFE-CYCLE ASSESSMENT

2.0 Introduction

This chapter is a primer on pavement LCA that provides the reader with a foundation and context for later chapters of the document, which explore each phase of the LCA process in further detail. This primer introduces the principles, purpose and details of the LCA process and defines the most important terminology. Existing LCA standardization is described, and steps are provided to begin including LCA concepts into decision-making processes by implementing "life-cycle assessment thinking." The chapter closes with an introduction to the various potential applications of LCA for pavement owner-agencies and their industry/market partners.

2.1 Origin of LCA

The precursors to LCA were originally developed in the late 1960s to analyze air, land and water emissions from solid wastes. The principles and applications were later broadened to include chemical emissions and use of energy and resources, with a focus on consumer products and product packaging rather than complex infrastructure systems (Hunt and Franklin 1996; Guinée 2012). Between 1990 and 2000, developments shifted to the creation of full-fledged, impact-assessment methods and the standardization of LCA methods by the ISO (SAIC 2006). In the transportation area, LCA topics have included: assessment of asphalt binder and cement production; evaluation of low-carbon fuel standards for on-road vehicles; examination of transportation networks; and examination of interactions between transportation infrastructure, vehicles and human behavior, amongst other topics.

2.2 Purpose of LCA

LCA provides a comprehensive approach to evaluating the complete environmental burden of a particular product (such as a ton of aggregate) or more complex systems of products or processes (such as a transportation facility or network), examining the most significant environmental inputs and outputs over its life cycle, from raw material production to the end of the product's life. A generic model of a production life cycle for LCA is shown in figure 2-1. As can be seen, the life cycle begins at the acquisition of raw materials, proceeds through several distinct stages (material processing, manufacturing and use), and terminates at the product end of life (EOL).

LCA can be used for a variety of purposes, including (Harvey, Meijer, and Kendall 2014):

- Identifying opportunities to improve the environmental performance of products at various points in their life cycles.
- Informing and guiding decision makers in industry, government and non-governmental organizations for a number of purposes, including strategic planning, setting priorities, product or process design selection, and redesign.
- Selecting relevant indicators of environmental performance from a system-wide perspective.
- Quantifying information concerning the environmental performance of a product or system (e.g., to implement an eco-labeling scheme, make an environmental claim, or produce an EPD statement).

Comparisons of LCA results can guide decision makers towards making choices that reduce environmental impacts (Van Dam et al. 2015). Moreover, LCA can be used to identify trade-offs in decision making by facilitating the evaluation of life-cycle stages and multiple environmental indicators. LCA is an approach for investigating the consequences of changes that, when properly applied, considers system-wide effects and the entire life cycle. If the pavement LCA does not consider all significant life-cycle stages and all appropriate environmental indicators, the resulting policies, regulations and specifications that are intended to reduce environmental impacts may have unintended negative consequences. This risk is greatest when changes are made to one system part or life-cycle stage without evaluating the effects of the changes on the rest of the system and the other life-cycle stages.

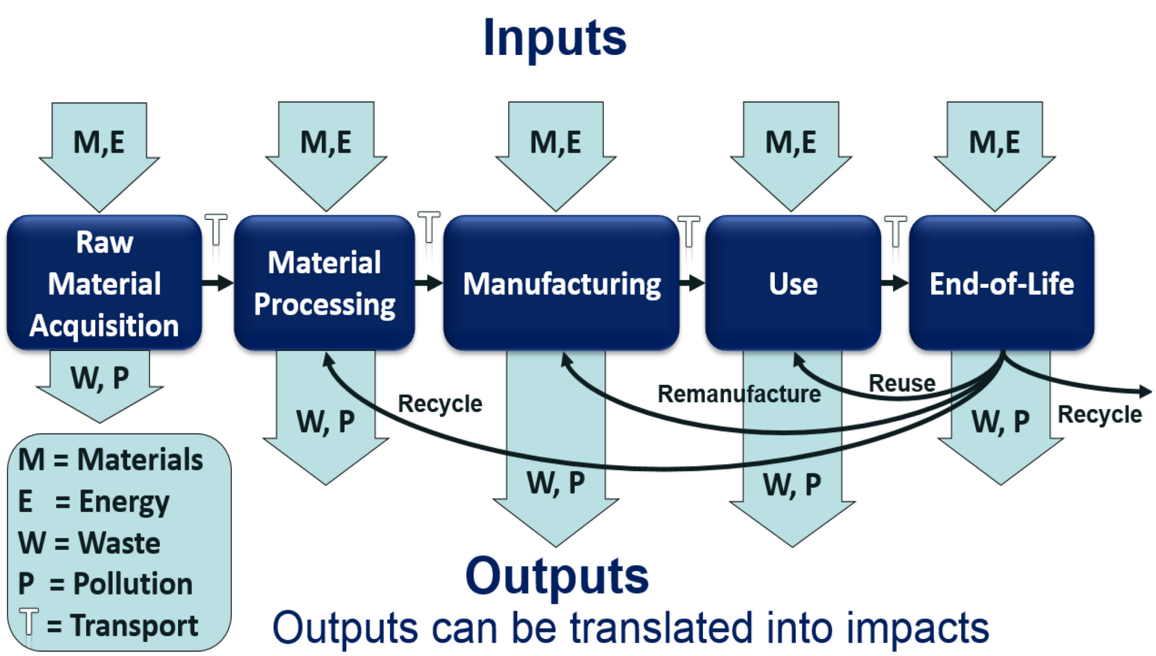

Figure 2-1. Generic life cycle of a production system for LCA (Kendall 2012).

2.3 Pavement Life Cycle

The pavement life cycle includes the material production, design, construction (new construction as well as preservation, maintenance and rehabilitation activities), use, and end-of-life stages associated with a pavement structure. These stages and some typical inputs and outputs for pavement are shown in figure 2-2, with additional discussion provided in the following sections.

2.3.1 Material Production

Modeling the material production stage requires that each material input to the pavement system be characterized by an LCI that includes the following processes: raw material acquisition, material production (i.e., all transformation processes from raw material to finished material or product), mixing processes (e.g., in asphalt or concrete plants), and transportation of raw or finished materials between stages. As is expected in all LCAs, the inputs to these processes should each be modeled from a life-cycle perspective and should include the LCI of the background processes as well (e.g., in addition to accounting for the foreground process of direct energy consumption, the LCI of the background processes for the production of the energy should be included).

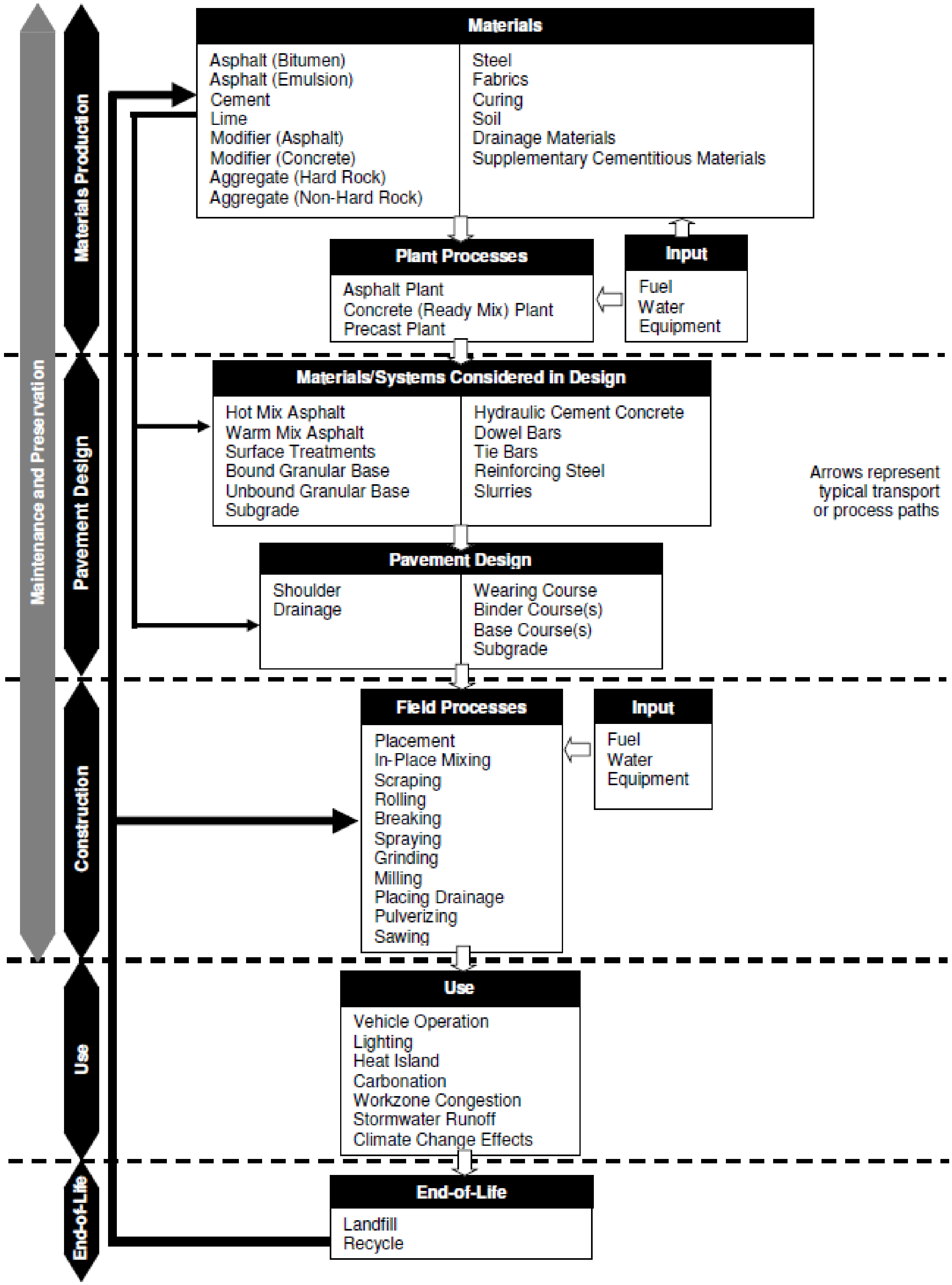

Figure 2-2. Representation of pavement life-cycle stages (UCPRC 2010).

2.3.2 Construction, Preservation, Maintenance, and Rehabilitation

The modeling of these stages requires that the following processes and impacts be considered:

- Equipment mobilization and demobilization (transport of equipment to and from the project site).
- Equipment use at the site.
- Transport of materials (including water) to the site.
- Transport of materials from the site for final disposal, reuse, or recycling.
- Energy used on site (e.g., lighting for nighttime construction).
- Changes to traffic flow, including work zone speed changes and delay and diversions where applicable.

In addition, changes to traffic over time should be considered in either the baseline modeling or a sensitivity analysis. These considerations should include changes in both traffic growth and traffic composition (i.e., vehicle type mix and technology) (UCPRC 2010). Many studies exclude the consideration of equipment manufacturing and capital investments in construction-related production facilities. That is an acceptable practice, but the exclusion or inclusion of each item must be explicitly stated so that the boundaries of the analysis are clear which then enables the interpretation of the analysis results in the appropriate context.

2.3.3 Use

Figure 2-3 illustrates various pavement characteristics and their impacts on the use phase of the pavement life cycle. Many of these relationships are the focus of current research.

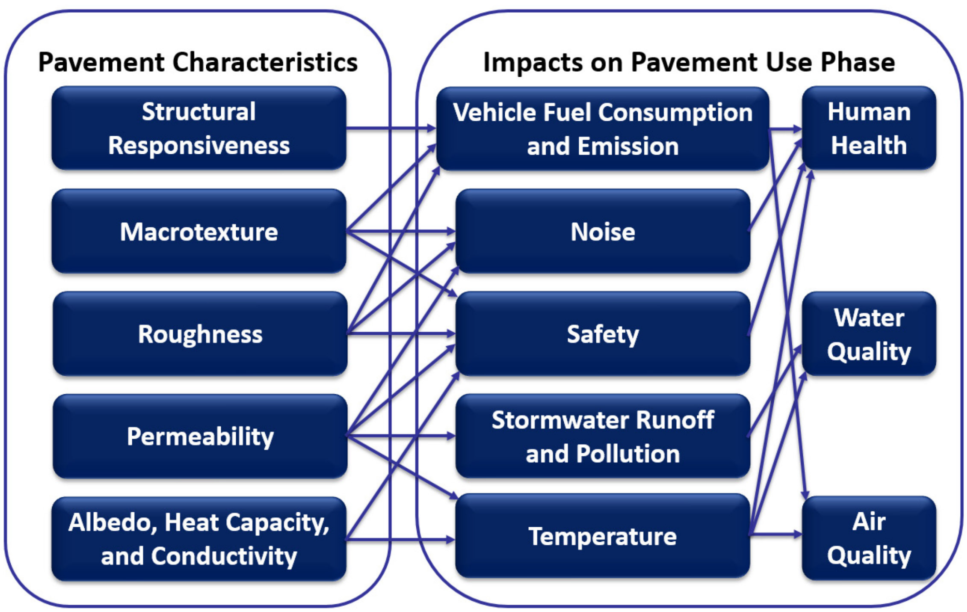

Figure 2-3. Selected pavement characteristics and their impacts on use-phase objectives (Van Dam et al. 2015).

These characteristics and their effects are summarized below:

- Pavement roughness, macrotexture and structural response can all affect vehicle fuel consumption and, as a result, have potentially significant environmental impacts.
- Pavement surface texture, roughness and other characteristics affect the intensity and frequency spectra of noise generated from tire-pavement interaction. This noise may impact humans inside of vehicles as well as human and animals within the acoustical range of the vehicles operating on the pavement.
- Pavement transverse profile, surface texture and permeability affect surface friction and the potential for hydroplaning, which can, in turn, impact pavement safety.
- The permeability of the pavement system impacts storm water runoff volume and flow rates. Pavements that are partially or fully permeable can reduce peak flow rates by holding precipitation within the pavement structure and slowly releasing it to the environment. This can reduce pollution flow into receiving water bodies and moderate resulting changes in the temperatures of those waters.
- The albedo (reflectance), heat capacity and thermal conductivity of the pavement all can affect the absorption of solar energy into the pavement and the emission of reflected and thermal energy from the pavement. These processes can potentially have both negative and positive impacts on energy consumption (through building and vehicle cooling/heating systems), air quality and human health (depending on a number of factors). In some applications, the albedo of the pavement may also have an impact on the energy needed for nighttime lighting and the visibility of pavement markings (safety considerations).

Decisions that impact the selection of these key pavement characteristics must recognize and consider many trade-offs, including many that affect important safety issues. It also must be recognized that many use phase effects are not yet well quantified; thus, considerable uncertainty exists, particularly when considering long analysis periods (e.g., 50 years or more).

2.3.4 End of Life

At pavement EOL (as well as during some rehabilitation activities), materials often become available for recycling, reuse or disposal. Just as in the other life-cycle stages, data are analyzed with respect to the EOL phase concerning equipment use and related fuel consumption, the reuse of materials, and the “production” of recycled materials like reclaimed asphalt pavement (RAP) or recycled concrete aggregate (RCA). Recycled materials are typically used in new pavement construction projects in the base or the pavement surface layers, and may be used in project fill and other applications. In rare circumstances, materials may be transported to a landfill for disposal.

In LCA, pavement recycling and reuse present a challenge concerning the partitioning or allocation of impacts and benefits between the originating pavement project and the receiving pavement project. One example is associated with the use of RAP, which can be used in significant quantities to replace aggregate and binder in new asphalt pavement. In this case, the question arises as to how much of the associated environmental benefit is allocated to the older pavement (or to the industry producing the recycled material) and how much to the new pavement being constructed. Allocation issues can also cross industry boundaries, such as when fly ash, a "waste" product generated from the burning of coal in electrical power plants, is used as a desirable cementitious material to replace portland cement in concrete.

Although there are several methods of allocation, there is currently no consensus on how to perform these allocations for the recycling of pavement materials. A general consensus among LCA practitioners and those involved in evaluating products and systems is that the allocation rules should be set up using the following criteria:

- Incentivize practices that reduce environmental impact.
- Prevent double counting of credits and the omission of important items.
- Reflect what is actually happening as closely as possible to ensure fair treatments of all stakeholders.
- Be transparent so that all parties can understand how allocations are performed and how they influence the results.

2.4 The LCA Process

LCA invites practitioners to use a systems-based approach that includes the full life cycle of a material, product, pavement or pavement system (i.e., "from cradle-to-grave"). However, it should be noted that LCA can also be applied to only selected life-cycle stages (e.g., "from cradle-to-gate"), depending on the goals and objectives of the LCA.

For pavements, the life cycle is typically defined to include the material extraction and production, construction, use, maintenance and rehabilitation (M&R), and EOL phases. Each of these stages is affected by the pavement design, which results in the selection of pavement structural layers and materials that, along with construction quality, determine the performance of the pavement for the given traffic, climate and native soil.

The general LCA process is described and governed by a series of standards produced by the ISO. The overarching requirements and guidelines are presented in the ISO 14044, *Environmental Management – Life-Cycle Assessment - Requirements and Guidelines* (ISO 2006b). From this standard, and as shown in figure 2-4, an LCA study consists of four phases, which are briefly described in the next sections and expanded upon in subsequent chapters:

1. Goal and Scope Definition.
2. Inventory Analysis.
3. Impact Assessment.
4. Interpretation.

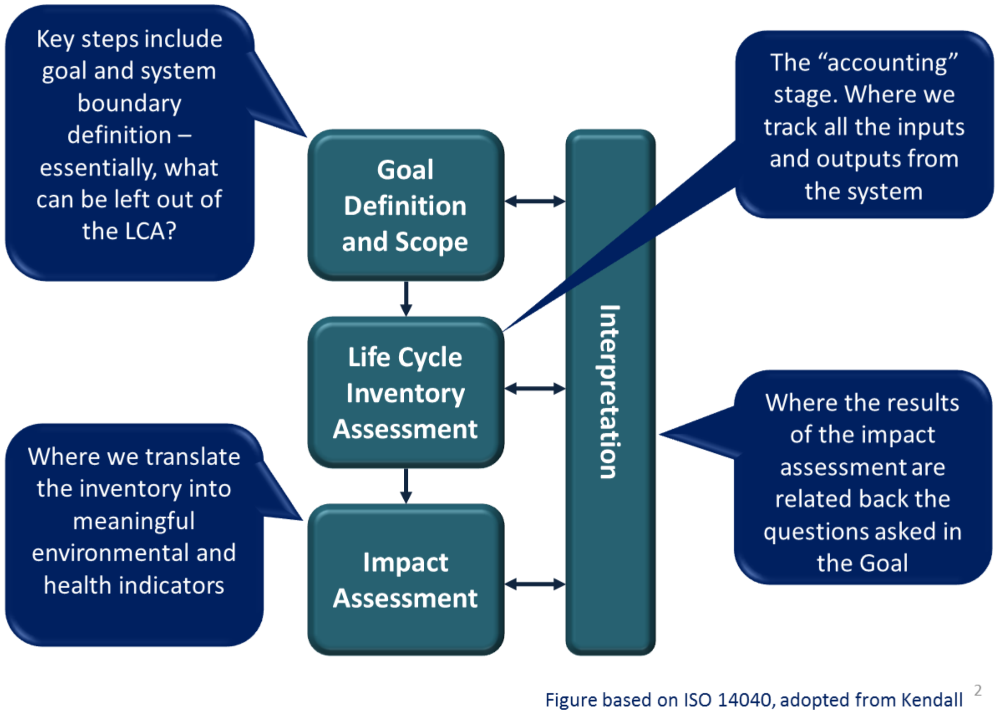

Figure 2-4. Illustration of the life-cycle assessment framework (Kendall 2012).

2.4.1 Goal and Scope Definition (see chapter 3)

The first phase in an LCA is the definition of the assessment goals and scope. These help to determine the key features of the analysis, including the depth and breadth of the LCA, which can vary considerably with the overall goals. Some of the key items that are considered include:

- **Goal**. Goals for an LCA must first be set by the organization performing the LCA in order to determine the type of study, the scope and the approach for assessing impacts and making decisions. Goals will likely differ between agencies, depending on their overall environmental objectives, policies, laws and regulations, all of which should be based on the environmental values of the agency that produces them.
- **Scope**. The scope of an LCA defines the system analysis boundary (i.e., what is and is not to be included in the LCA). The scope should address the life-cycle stages and processes to be included, identify the geographic and temporal boundaries of the analysis, define the functional unit of analysis, and define the required data quality. The selected scope should depend on the established LCA goals. The following are important elements that are defined in the scope:
  - **Functional Unit**. The functional unit describes what is to be studied by defining the physical unit and performance specifications that must be met. For pavement LCA, the functional unit might be a particular length of pavement with a specific geometry (e.g., a certain number of lanes and shoulders of a specified size) that meets the acceptance criteria set by the responsible agency over a specified length of time. All of the LCA results will be expressed against this functional unit, which can be considered to be a normalizing step.

– **Analysis Period**. This is the period of time addressed by the LCA. Selection of the analysis period is important for considering the impacts of changes in pavement performance, vehicle technologies, energy sources and traffic volume and composition, and more, over time. The analysis period should be long enough to capture the next rehabilitation or other major event whose timing is influenced by the current decision. Most LCA studies implicitly assume that current technologies and practices will remain somewhat constant over time and can be modeled forward (Harvey, Meijer, and Kendall 2014).

2.4.2 Inventory Analysis (see chapter 4)

The second phase of an LCA, the life-cycle inventory analysis phase, is where environmental flows (e.g., inputs of material, energy and resources, and outputs of waste, pollution and co-products) are identified and quantified for the system being studied. To perform an inventory analysis, a model of the process being analyzed is set up using the functional unit and system boundary definitions. The flows of materials and energy into the process model are then identified and calculated for each life-cycle stage, as are the waste and pollution flows coming out of the process (see figure 2-1). Collectively, these data are typically referred to as the life-cycle inventory (LCI). For a typical asphalt or concrete mixing plant, typical flows include: energy consumption in the form of electricity, fuel oil, or natural gas; raw material consumption in the form of aggregates, asphalt binder, cementitious materials, and water; and output flows, such as emissions and waste. Typically, all of these inputs and outputs are traced all the way back to their origins. For aggregates, the origin is commonly the quarrying processes; for natural gas, origin inputs include the processes of setting up the gas well and delivering the gas. Similar considerations must be used for each flow (Harvey, Meijer, and Kendall 2014).

Data for these processes can be obtained from a number of sources, including existing public data, commercial data available for purchase, and even project-specific, on-site data collection. In practice, a combination of these data collection approaches may be necessary, depending upon the LCA scope, and the collected data will often require appropriate spatial and temporal corrections. Some examples of approaches to data collection are included in recent literature (e.g., Weiland and Muench 2010; Mukherjee, Stawowy, and Cass 2013; Santero et al. 2011; and Wang et al. 2012).

No matter what data are used, it is important to report the type of data and their quality in order to identify which data are influencing the conclusions of the assessment, as well as to perform sensitivity analysis on those inventory data sets that are the most influential. General guidance on data quality and data-quality indicators is available from ISO (2006a; 2006b).

2.4.3 Impact Assessment (see chapter 5)

The life-cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to develop a better understanding of the environmental significance of the LCI by translating environmental flows into environmental and human health impacts. Impacts generally fall into the broad categories of:

- Depletion of resources.
- Impacts on humans.
- Impacts on nature (ecosystems).

LCA studies usually include a selection of impact categories that are most relevant to the specific project goal and scope, and can range from a narrow focus on energy and energy-related emissions to a full set of impact categories. A list of typical impact categories is included in table 2-1. The most commonly used impact categories in the U.S. are based on the TRACI ("Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts") impact assessment methodology developed by the US Environmental Protection Agency (EPA). The most recent version of this tool, TRACI v2.0, was released in 2012 (Bare 2011; EPA 2012). The most widely used global impact assessment method is the CML (Center for Environmental Studies at the University of Leiden, the Netherlands) methodology (Guinée et al. 2002), which was most recently updated in April 2015.

2.4.4 Interpretation (see chapter 6)

In the final phase, interpretation, the overall results are summarized and discussed as a basis for conclusions, recommendations and decision making in accordance with the defined goals and scope. Proper LCA practice, as defined by ISO 14044, includes an interpretation phase where the results are presented for the functional unit, the major environmental contributions are identified and explained in terms of where the environmental impacts are most pronounced, the data uncertainty and variance are noted, and sensitivity analyses are conducted for the most important methodological assumptions.

Table 2-1. Typical LCA impact categories.

Group	Impact Category
Energy use	Fuel, nonrenewable[1] Resources, nonrenewable Resources, nonrenewable, secondary Fuel, renewable Resource, renewable Resource, renewable, secondary
Resource use	Resource, renewable Resources, nonrenewable[2]
Emissions	Climate Change[1, 2] Ozone layer depletion[1, 2] Acidification[1, 2] Tropospheric ozone[1, 2] Eutrophication[1, 2]
Toxicity	Human toxicity[2], respiratory[1] Human toxicity, carcinogenic[1] Human toxicity, noncarcinogenic[1] Ecotoxicity[1], fresh water[2] Ecotoxicity, marine water[2] Ecotoxicity, soil[2]
Water	Fresh water use
Waste	Hazardous Nonhazardous

[1] Part of TRACI

[2] Part of CML

Uncertainty in LCA results is a natural outcome of inherent data variability, input uncertainty and model imprecision (ISO 2006b). Pavement LCAs should include an analysis of uncertainty in the functional unit, analysis period, LCI data, system boundary assumptions, and impact assessment. Some examples of the sources of uncertainty include limitations in the data used, uncertainty in predicting future changes in traffic and technology, and assumptions in the allocation of impacts for reused and recycled materials.

ISO 14044 states that the most important aim of LCA studies is that they be reported transparently so that readers can review the goals, scope, and conclusions of the study. ISO 14044 also requires an independent review for LCA studies that compare alternatives; a review panel is typically convened for that purpose (Harvey, Meijer, and Kendall 2014).

2.5 Standardization

The need to standardize the LCA methodology to ensure consistency in the process led to the development of LCA standards in the early 1990s by the ISO, as documented in their 14000 family of standards. Key standards related to LCA in this series are:

- ISO 14025, *Type III Environmental Labels and Declarations - Principles and Procedures* (ISO 2006c).
- ISO 14040, *Environmental Management – Life-Cycle Assessment - Principles and Framework* (ISO 2006a).
- ISO 14041, *Environmental Management – Life-Cycle Assessment - Goal and Scope Definition and Life-Cycle Inventory Analysis* (ISO 1998).
- ISO 14042, *Environmental Management – Life-Cycle Assessment – Life-Cycle Impact Assessment* (ISO 2000a).
- ISO 14043, *Environmental Management – Life-Cycle Assessment – Life-Cycle Interpretation* (ISO 2000b).
- ISO 14044, *Environmental Management – Life-Cycle Assessment Requirements and Guidelines* (ISO 2006b).

This document is aligned with ISO 14000 standards for the following reasons:

- The ISO 14000 family of standards is generally accepted worldwide by material-producing and product-manufacturing industries as the primary standard describing LCA.
- The ISO 14000 family of standards promotes completeness and transparency of LCA studies based on worldwide consensus for best practice.
- Adhering to the ISO 14000 family of standards leads to consistency and compatibility of practice across industries, which results in information that is easier for consumers of LCA studies to use effectively and efficiently.

While the ISO 14000 family of standards (particularly ISO 14040 and 14044) define a commonly accepted standard method for LCA, specifics can vary greatly from one application to another. As a result, each industry must develop its own approaches for the implementation of the ISO standards.

The LCA approach developed and used by an industry to produce EPDs or other types of "ecolabels" is called a Product Category Rule (PCR), and the applicable ISO standard is 14025 (ISO 2006c). A commonly cited set of LCA standards specific to building materials is published by the European Committee for Standardization under Technical Committee 350 (Sustainability of Construction Works) and includes a standard for EPDs published as EN15804 (CEN 2013). These and other standards and guidelines for LCA are referenced throughout this document for application to pavement LCA.

Examples of the benefits of standardization include the consistent modeling of cement for concrete, whether it is used in buildings or for pavements, and the consistent modeling of the use of oil, whether it is used as a pavement material resource or as an energy resource. Alignment with and adherence to the ISO standards aims to improve the general practice of LCA, providing consistency across different applications, including pavement LCA.

2.6 Approaches for Implementing LCA "Thinking"

It is recognized that LCA concepts are new to many agencies and potential users. The following steps can be taken to begin including LCA concepts in decision-making processes even without conducting a full LCA:

1. Identify questions to be answered and specific environmental goals to be achieved. In many cases, the questions regard the impact of a change in policy or the design of a specific project as compared with current practice (the "base condition").
2. Define system boundaries and identify items that are the same across a comparison study so that they need not be considered in the analysis.
3. Define the functional unit and the approach required for sensitivity analyses for evaluating a policy, including the determination of specific project variables and a number of cases that span the expected ranges of conditions.
4. Identify the types of operations and materials that occur within the system, and determine how their types and numbers change for the options being considered. A comparison of units of something used or consumed may be enough to identify the net effects of the proposed change on the system, particularly if only one type of input or output changes.
5. Identify appropriate environmental data sets (i.e., life-cycle inventory data) needed and continue with the LCI, impact assessment and interpretation phases of the LCA as described previously.

The completion of the first four items of this process often help to determine whether a full LCA needs to be completed, or whether it is clear that one alternative will have a reduced environmental impact (Harvey et al. 2013).

2.7 Potential Agency Application of LCA

The current use of LCA in pavement applications is rather limited and only a few agencies are working to apply LCA in a consistent way. Still, there are a number of examples that illustrate how LCA can be used for a variety of purposes. Some specific examples of applications of pavement LCA by agencies in North America are shown in table 2-2, the most common of which include:

- Selection of a material or pavement structural design in conjunction with LCCA (example 1.a).
- Evaluation of the impacts of potential changes in a policy or specification (example 2.e.).
- Development of LCA tools for screening or detailed LCA for the scoping or design of a project (example 2.h).
- Evaluation of scenarios for network-level decisions and strategies for preservation, maintenance and rehabilitation (example 3.i).
- Development of pavement material EPDs (example 4.k).

2.8 Summary

This chapter presents a brief primer on the principles, components, and application of LCA for pavements. The application of LCA can help support decision making regarding changes to policies and practices to reduce the impacts of pavements on humans and the environment while identifying potential unintended negative consequences. More detailed information on LCA as it applies to pavements is available elsewhere (e.g., SAIC 2006; Kendall 2012; Harvey, Meijer, and Kendall 2014; and UCPRC 2010).

Table 2-2. Application of LCA for agencies.

ISO Use Case (Application)	Example
1. Identifying opportunities to improve the environmental performance of products at various points in their life cycle.	a. Pavement material or structural design selection (in conjunction with LCCA). b. Pavement material procurement optimization. c. Evaluation of the potential benefits of the use of higher recycled content or on-site recycling of pavement materials.
2. Informing and guiding decision makers in industry, government, and nongovernmental organizations for a number of purposes, including strategic planning, priority setting, product or process design selection, and redesign.	d. Identify the effects of potential changes in a project. These are typically comparisons of alternatives for pavement material types and sources, pavement structural designs, pavement type, design lives, future maintenance and rehabilitation scenarios or other types of project-specific plans and specifications. The project can be for a new pavement, rehabilitation or maintenance for a single project. This type of study would typically be done by or for a project designer or planner who is comparing alternative strategies for treatment of an existing pavement or constructing a new pavement. An example would be considering the effects of an improvement in the maintenance and rehabilitation programs to extend the pavement service life or improve smoothness. e. Identify the effects of potential changes in a policy. Studies used for policy assessment usually consider changes in specifications, design methods, standards, or project- or network-level goals that will be applied across all projects and all scenarios for network management. The assessment is often performed by completing an LCA study on a set of example cases selected to sufficiently characterize all expected applications of the change to projects or the network for the purposes of deciding whether or not to make the change. This type of study would typically be done by a pavement engineer or planner to answer questions posed by internal or external stakeholders before moving ahead with changes. f. External communication of improvements in pavement life-cycle design and use by comparing environmental performance over time (i.e., current project vs projects from before). g. LCA-based environmental performance as part of the procurement process in the design-bid-build (low-bid) project-delivery system, as it is being used in some European countries. h. Development and application of LCA tools for screening or detailed project-level LCA.
3. Selecting relevant indicators of environmental performance from a system-wide perspective.	i. Identification of relevant and significant indicators over which an agency has control from a network-level LCA approach. This type of study focuses on decisions or scenarios regarding the timing and types of preservation, maintenance, rehabilitation and reconstruction treatments for a set of pavements that are managed as a network. This type of study is typically performed by or for pavement management staff in order to answer questions posed to the pavement management unit internally or by external stakeholders regarding the entire network or subsets within the pavement network. j. Prioritize LCI database development at either the state (regional) or national level.
4. Quantifying information on the environmental performance of a product or system (e.g., to implement an eco-labeling scheme, make an environmental claim or produce an environmental product declaration statement).	k. The development of an EPD following the PCR for the product that is the subject of the EPD. l. While some pavement materials used in pavement LCA are in the process of developing (or have published) EPDs, there are currently no programs available in the U.S. market for environmental claims on a pavement structure level. It is generally expected that this case will not be common in North America because pavement structures are generally individually designed for unique conditions for each project. They are also often designed by the owner (rather than the producer) without knowing the precise sources of the construction materials that will be used and, therefore, cannot be assessed generically with an EPD.

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CHAPTER 3. GOAL AND SCOPE DEFINITION

3.0 Scope of Pavement Systems

It is recognized that sustainability is a system characteristic, and pavements are but one part of the transportation system. The pavement system is defined as the structure constructed above the native undisturbed subgrade soil, typically constructed in distinct layers and including compacted or stabilized subgrade, bound or unbound subbase(s)/base(s), and the wearing surface. Broadly, this encompasses pavement structures in a number of different facility types, such as highways, streets, roads, shoulders and parking areas. The focus of this document is on pavement structures in mainline and shoulder applications for highways and roadways that are typical of those managed by State highway agencies. Furthermore, only hard surfaced roadways are considered, including those surfaced with various types of asphalt concrete (AC) and hydraulic cement concrete (HCC). For the purposes of this document, all surfaces constructed with asphalt materials are generically referred to as "asphalt" pavements, whereas all surfaces constructed with HCC are generically referred to as "concrete" pavements.

There are a number of items related to highways and roadways that are not included or considered in this document; examples include:

- Planning.
- Capacity.
- Roadway striping.
- Roadway signage and message boards.
- Barriers and other safety appurtenances.
- Ice and snow management.
- Roadside management.
- Drainage structures.
- Bridges and other structures.

3.1 Introduction

The first step in any LCA study is to define the study goal(s) and scope. A precise definition of the goal is needed to clearly identify system boundaries and the functional unit that will be used throughout the LCA study, including the subsequent phases of establishing the LCI, conducting impact analyses, and effectively interpreting and reporting the results. A well-defined goal helps to determine which processes and flows within the system boundaries are to be included or excluded from the study.

Once the goal of the study is defined, the scope is developed to include the following items (ISO 2006a; Harvey et al. 2010):

- Definition of the product(s) to be studied in terms of the function(s) or service(s) provided.
- Definition of the *functional unit* and *analysis period*, which are needed to relate the impacts to a unit of service over a defined period of time.

- Determination of the *system boundaries* and *life-cycle stages*, which are needed to decide which material flows and emissions are included in the study and which ones are excluded.
- Selection of the *allocation procedures* that are to be used when assigning *flows* to multiple products that come from the same process, or to multiple processes that are used for a single product.
- Selection of the *indicators* and their subsequent *interpretations* to be used to determine progress toward the goal, including *environmental indicators* of selected aggregated *flows* from the life-cycle inventory and *impact indicators* calculated for selected *impact categories* using an *impact assessment methodology*.
- Documentation of the *limits of the study* in terms of the scope definition (particularly what will be left out of the study and why), limitations of data availability and quality for each life-cycle stage, which indicators have been selected and which have not (and the resulting limitations on the ability to calculate impacts), and the limitations of the sensitivity analysis.
- Identification of the *data requirements* and *data-quality requirements* to ensure that data used to determine flows, calculate impacts and perform *sensitivity analysis* of the interpretation of the results are sufficient to meet the goals of the study.
- Determination of the *critical review* process needed to meet the goals of the study and the expectations of the intended audience for outside review.
- Determination of the *reporting* requirements (type and format) to appropriately convey the results to the intended audience.

The first three items are discussed in detail in this chapter. Short introductions to the remaining items are also provided in the context of how they should be considered in the goal and scope definition process. More details on data inventories and allocation, impact assessment, interpretation, critical review, and reporting are presented in chapters 4, 5, 6, 7 and 8, respectively.

The development of the goal definition and scoping document works best if it explicitly follows a process of the type shown in figure 3-1. Decisions in preceding phase of the goal and scope definition are usually necessary in order to proceed to the next step in the scoping process. Assumptions and limitations should be documented in each step of the goal-setting and study-scoping processes for use in steps 7 and 8 shown in figure 3-1.

The process for goal and scope definition shown in figure 3-1 should be used for all LCA studies. Different levels of complexity were discussed in chapters 1 and 2, including benchmarking studies, LCA studies with a small set of impact category indicators and LCA studies with a full set of indicators. As defined for this document, benchmarking studies are generally considered to include all of the steps shown in figure 3-1 except that they will generally not include impact indicator calculation.

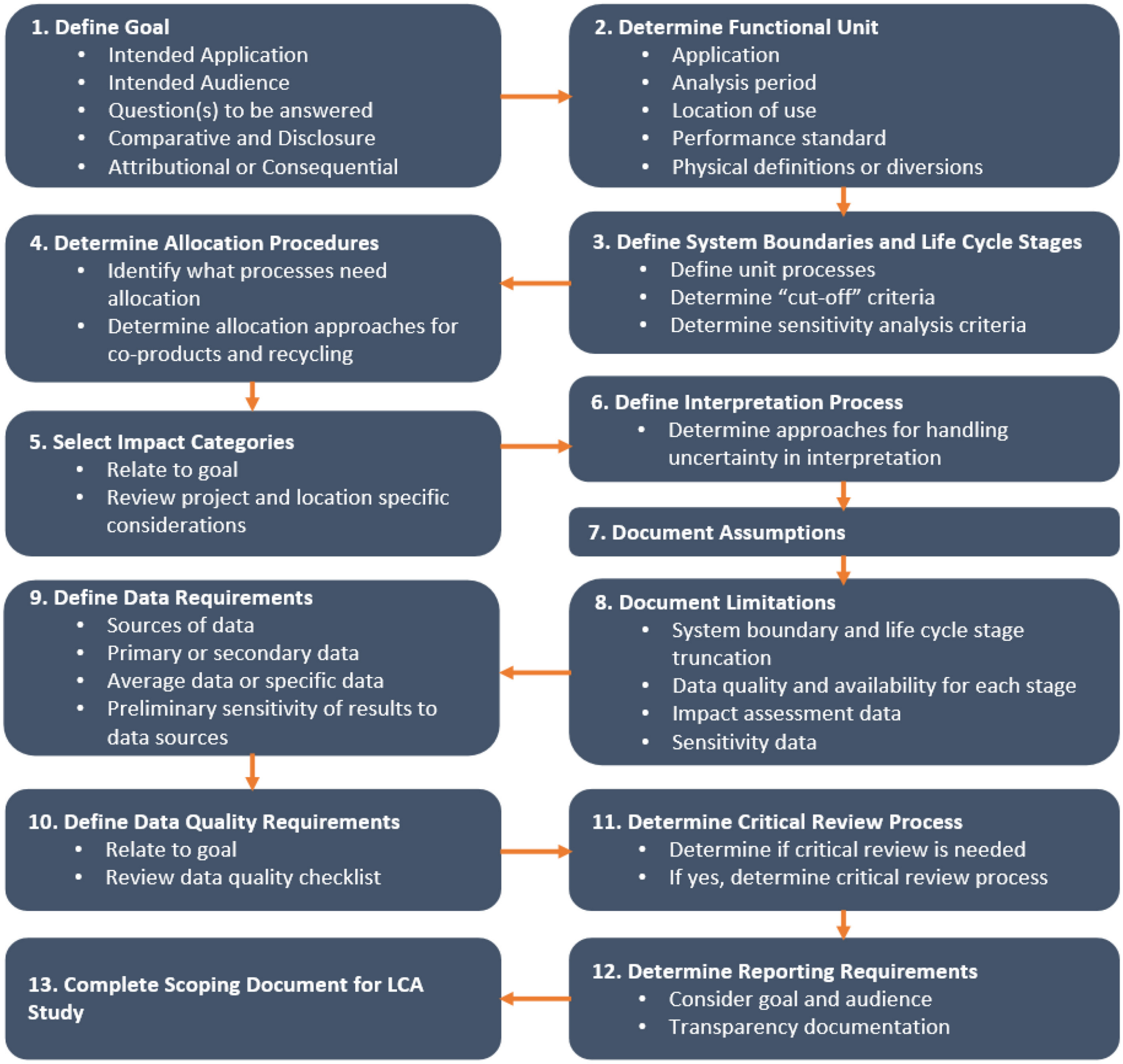

Figure 3-1. Flow chart for developing goal definition and scoping document for LCA studies.

3.2 Guidance

The following sections provide guidance on each step involved in the development of the goal definition and scoping document for LCA studies.

3.2.1 Define Goal

Common applications for pavement LCA studies are shown in table 2-2. It is often helpful when identifying the goal of the study to refer to those generic application types. The matrix of application type and complexity level is referred to throughout this and subsequent chapters.

Items that should be considered when defining the goal of the study are:

- Intended application.
- Intended audience.
- Question(s) to be answered.

- Whether the study is intended for comparison with alternatives (referred to as a *comparative* study) or disclosure for a single decision or product.
- Whether the study approach is *attributional* or *consequential.*

The LCA study sponsors should stipulate the goal of the study in terms of a question. The LCA practitioner should then determine whether this is a single product/decision LCA or a comparative LCA, and then whether the study is attributional or consequential (see sidebar). Thus, the goal of the pavement LCA can be any of the following four options:

1. A single product or system attributional analysis to determine the flows and impacts of the product or system.
2. A comparative attributional analysis, comparing the flows and impacts of two or more products or systems.
3. A single product or system consequential analysis that considers how flows and impacts will change within and beyond the system in response to decisions.
4. A comparative consequential analysis, comparing the changes in flows and impacts within and beyond the system boundary due to alternative decisions.

Examples of the four types of studies are shown in table 3-1.Most pavement LCA studies are attributional because most of the common uses of LCA in pavement applications rely on assumptions that the systems in which pavements are built and operated and the socio-economic and physical systems that support pavement systems do not change substantially within the context of the question to be answered.

Attributional and Consequential LCA Studies

Most pavement LCA studies are attributional*, meaning they are based* on *estimating the "flows and potential environmental impacts of a specific product system typically as an account of the history of the product" (ISO 2006a). This is useful in understanding the impacts of a pavement project or network, or for comparing alternatives for a pavement project (i.e., the choice of pavement type) that will not change the systems that they interact with, such as inducing price changes or consumer behavior changes.*

Attributional LCAs may not be appropriate when considering future policies or technologies that change the status quo of the overall systems inside and outside the project or network. These types of change-oriented studies should take a consequential approach.

Consequential LCAs assess the environmental impacts of changes to an evaluated system. This can be useful in evaluating system-wide impacts. Additionally, consequential LCA can be useful for infrastructure and planning studies that evaluate decisions that have longer-term and more far-reaching consequences not considered in attributional studies. System boundaries for consequential LCA should be set to capture "unintended consequences" and interactions of the pavement processes being assessed with other systems.

Consequential LCA is mostly used for decision support at regional or national levels, and focuses on the environmental impacts induced by decisions. Consequential LCA often requires knowledge of the sensitivity of socio-economic and physical processes to the intervention being studied for the pavement systems and all other systems that will change (and their interactions).

The sponsors and the LCA practitioner should review the goal definition statement to be certain that it is fully understood and that there is agreement on its accuracy and its representation of the problem under investigation before moving forward with the next steps of the LCA. The goal will drive the scope of analysis, which may not require a full life-cycle approach. For example, the analysis for a particular material may be a "cradle-to-gate" or a "cradle-to-landfill" analysis. The LCA study should be redesigned if the goal changes.

Table 3-1. Examples of the four different types of pavement LCA studies (single product vs. comparative and attributional vs. consequential).

Question	Type of LCA Study	Intended Application	Intended Audience
What resource flows are used in producing a pavement material and what are the resulting emissions and impacts?	Single product attributional	EPD for the given product.	Customers who buy the product, the company commissioning the EPD who may use it for product design and improvement, and LCA practitioners answering other questions who need inventory data provided by the EPD.
Which of two alternative types of rehabilitation have the least resource use and environmental impacts over a set of indicators?	Comparative attributional	Decide which alternative should be used based on environmental impact and resource use.	People deciding which alternative to use and those reviewing the decision.
What are the fuel use, local air pollution, and damage to pavement caused by truck transportation required by alternative locations for recycled materials stockpiles?	Comparative attributional (benchmarking study, no impact indicators calculated, only life-cycle inventory for flows of interest)	Select best locations for stockpiling and delivering recycled materials to construction sites.	Construction planners and project managers, local residents, and permitting and other government agencies.
What are the changes in environmental impact for a region if pavement maintenance and rehabilitation budgets are permanently reduced by 20 percent and those funds are instead put into transit and active transportation, assuming no change in the size of the pavement network? All systems that would be affected should be considered, including mode choice for freight and personal mobility, employment and travel demand patterns, vehicle type selection for rougher roads, vehicle maintenance and replacement time, freight damage, and energy type.	Single system consequential	Support planning decisions for allocation of transportation funding to meet environmental goals.	Regional policy makers, all affected stakeholder organizations, public.
What are the life-cycle environmental impacts of alternative new specifications for concrete and asphalt mix designs to include more recycled materials? Considering alternative uses of the recycled materials and the replaced cement and asphalt binder outside the pavement system, and changes in price due to changes in demand.	Comparative consequential	Determine whether the policy produces environmental benefits compared to the current specifications.	Policy decision makers, industry groups affected (within and outside of pavements).
What are the life-cycle environmental consequences of alternative pavement management treatment strategies in a treatment selection decision tree? Consider effects of alternate treatments on life-cycle costs, vehicle fuel efficiency, and changes in the cost of newly developed treatments if their use is increased substantially.	Comparative consequential	Reduce the environmental impacts of network within cost constraints.	Pavement managers and financial planners, affected industry stakeholders.

3.2.2 Determine Functional Unit or Declared Unit

The functional unit defines the system that will be studied and acts as the reference for scaling of input and output data in any of the life-cycle stages of the product or service (Kendall and Santero 2010, CEN 2013). The functional unit can be characterized by identifying the following items (which are discussed in detail below):

- Application.
- Location where it will be used.
- Physical boundary definitions and dimensions (referred to as the "unit").
- Performance standard.
- Analysis period.

For pavement systems, the functional unit should be a representation of the physical dimensions and the quantified performance of the pavement (Harvey et al. 2010), which aligns with the ISO 14044 definition that the functional unit is the "quantified performance of a product system for use as a reference unit" (ISO 2006a).

Whenever the goal of the study is the comparison of alternatives, it is essential that there is equivalence of the definitions of the functional units of the alternatives so that they can be compared without bias.

When the application of the product and its functional requirements are uncertain and not part of the goal and scope of the study, then a declared unit may be used instead of a functional unit. A declared unit can only be used when the scope of the LCA does not include all stages of the life cycle beyond delivery to the gate of the plant and, therefore, functional requirements for the stages will not be defined. The defined unit is typically defined in terms of its physical quantity (such as mass, length, area or volume) and does not include any definitions of functionality. Defined units are used for EPDs for materials which can be used in a number of applications and are used to provide LCI information for component materials of composite materials. The declared unit should relate to the typical (albeit not completely) defined uses of the material. (CEN 2013, EeBGuide Project 2012)

Application

The application will determine the characteristics and components of the system based upon the purpose that it is intended to serve. The application will have been determined when defining the goal and is derived from the context of the goal question.

Location of Use

The location of use will influence the definition of a number of other elements of the functional unit as well as later decisions, such as applicability of data, the importance of different impact category indicators and the interpretation of the results. The location can be easily defined for project-specific studies or when analyzing an entire network for a network-level analysis. The owner of the functional unit will influence the standards being applied, the technology used for materials, prevailing construction practices, and design methods and pavement management criteria, as well as regulatory standards that may be relevant to the LCA. More careful consideration of the location is needed when selecting a factorial of example projects for a policy analysis. For an EPD, the location will be for the location(s) where the product is produced. An EPD can be for a single site producing a material, or may be an average or model representing multiple sites (see chapter 5 for details).

Physical Boundary Definition and Dimensions of Functional Unit

The physical boundaries of the functional unit define the portions of the pavement structure to be considered part of the pavement system at the location(s) included in the study. The dimensions permit the determination of volumes, masses, surface areas and other quantities needed to perform the LCA.

In general, an LCA study of a complete pavement system needs to consider the processes within the entire physical boundaries of the pavement structure, including the surface, base, subgrade, shoulder and drainage system. However, if the goal of the LCA does not include the complete pavement system, then the system boundaries can be adjusted. For example, the physical boundaries may include the mainline pavement but leave shoulders and ramps out of the system (if they are the same for all alternatives being considered). Other choices to make when defining physical boundaries include whether or not to include all of the pavement layers. For example, if two alternatives for resurfacing are being considered, the layers that are not being touched by either alternative may be excluded and the slopes of fill sections may be included or left out, depending on the goal of the study.

Performance Standard

The performance standard for the pavement system(s) being evaluated is typically identified in terms of the design life, functional life or another functional criteria, such as roughness or specific levels of pavement distress. The performance standard should be appropriate for the application, location and physical boundaries of the functional unit.

An important aspect of a functional unit is to define the functional performance standard metrics that need to be met. This is usually accomplished by referencing performance metrics associated with the standards of an owner and a geographical area. For pavements, these will be the length of time (or, more likely, a specified number of traffic repetitions transformed to time) and performance in that time period for metrics such as specified levels of distresses and roughness, or other structural or functional condition measures. These metrics often vary between highway agencies, and agency definitions and requirements may change periodically.

Performance unit metrics can play a crucial role in study interpretation, especially in comparative LCAs where two different products offering the same service are compared. When the goal is a comparative study, ISO 14044 (ISO 2006b) states that:

> *In a comparative study, the equivalence of the systems being compared shall be evaluated before interpreting the results. Consequently, the scope of the study shall be defined in such a way that the systems can be compared. Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, and decision rules on evaluating inputs, and outputs and impact assessment. Any differences between systems regarding these parameters shall be identified and reported. If the study is intended to be used for a comparative assertion intended to be disclosed to the public, interested parties shall conduct this evaluation as a critical review.*

The performance standard will also be needed to determine the expected performance characteristic metrics of the pavement (e.g., smoothness, distress, friction, reflectance and noise) during the analysis period.

Some metrics used in comparisons, such as ride quality measured by IRI (with any appropriate measurement technology adjustments), can likely be assumed to be comparable over some pavement decisions being considered. Other metrics may differ over decisions such as pavement type because they only occur on one type, such as faulting on jointed concrete pavement and rutting on asphalt pavement. In such cases, consideration of the agency's definitions of comparable states for performance metrics should be given in the defined study goal and scope, and comparisons of values for inherently different metrics, such as cracking severity levels in concrete and asphalt pavements, should be identified for potential consideration in sensitivity analyses.

For example, a performance standard for a project-level comparison of rehabilitation alternatives could include the required design life, with design life based on distress and roughness performance requirements for the materials, traffic and climate relevant to the location, the materials and construction standards and specifications of the owner, and expected future maintenance and rehabilitation interventions. For comparisons of alternative treatment scenarios in a network level LCA, the performance standard could include the agency's decision tree criteria for treatment, network-level distress goals and budget constraints. For an EPD for a material used in pavement, the performance standard should state what specifications or standards the material will meet, and provide test data that will permit the audience for the EPD to determine what standards and specifications it will meet.

Analysis Period

For pavement LCA, recommendations for analysis period selection aim to capture the impacts of the current decision and its influence on subsequent maintenance/preservation treatments at least through the life of the next major rehabilitation or reconstruction treatment event. Yet care must be exercised to not unnecessarily increase the analysis period and subsequently raise the difficulty and uncertainty of predicting future events.

When different pavement design options are to be compared, the selected analysis period should be at least long enough to cover the life of the next major rehabilitation of the longest lasting system (and should preferably extend through the lives of several rehabilitation treatments or the first reconstruction) so that the effects of the current alternative on subsequent decisions are considered in the analysis (see the commentary on analysis periods in section 3.3.2 for application examples of this principle). A simple truncation rule should be applied to the fractions of lives left over at the end of the analysis period for shorter-lived treatments. This truncation rule amortizes the part of the life that is in the analysis period using a straight-line reduction in functionality from the time of initial construction until the next major treatment, as shown in in section 3.2.2

When one of the pavement systems or treatments in the LCA is extremely long lived, a maximum analysis period of 100 years is recommended. When the longest lived pavement system in the LCA will likely never receive a major rehabilitation or reconstruction and will receive only maintenance and preservation treatments (e.g., for a pavement handling very low traffic volumes), then a minimum 35-year analysis period is recommended (FHWA 1998).

A good practice for state highway agencies and other organizations with established LCCA guidance is to follow the same practices for selecting analysis periods for LCA, provided that they essentially follow the guidance provided by US DOT and this document. Definitions of maintenance, preservation, rehabilitation or reconstruction should follow established LCCA practices for the agency. The FHWA provides definitions (FHWA 2005), including updated definitions for preservation and maintenance at FHWA (2016).

Depending on its goal, the LCA study may consider less than the full life cycle of the pavement decision. For example, the goal may be to only consider the materials and construction stages, or only the use stage. Careful consideration should be given to analysis periods that do not extend beyond the functional life of the next major rehabilitation or reconstruction in any pavement LCA study. When such extensions are unavoidable, the reasons for not following the analysis period recommendations presented here should be explained in the Goal and Scope documentation.

3.2.3 Define System Boundaries and Life-Cycle Stages

Steps that must be taken to finalize the system boundaries and life-cycle stages are:

- Define unit processes.
- Determine cutoff criteria.
- Determine sensitivity analysis criteria.

Unit Processes

Unit processes refers to all processes that are part of the functional unit to be considered in the pavement LCA study. The system boundaries are the set of criteria specifying which unit processes are part of the system being analyzed and which are not (ISO 2006a). It is often helpful to describe the system using a process flow diagram showing the unit processes and their interrelations. Each of the unit processes included in the study should be defined in terms of:

- Where the unit process begins, in terms of the receipt of raw materials or intermediate products.
- The nature of the transformations and operations that occur as part of the unit process.
- Where the unit process ends, in terms of the destination of the intermediate or final products (ISO 2006b).

Cutoff Criteria

The system boundaries and life-cycle stages to be considered should be selected based on the goal of the study. Based on ISO 14044 requirements, deletion of life-cycle stages, processes, or inputs or outputs for a given process should only occur if the deletion does not significantly change the overall conclusions of the study. In addition, any decisions to omit life-cycle stages, processes, inputs or outputs should be clearly stated, and the reasons and implications for their omission should be explained.

The exclusion of life-cycle stages could lead to incorrect conclusions with significant unintended consequences. For example, the production of a particular material may have a low environmental impact, but its durability may not be good, leading to frequent replacement, or it may cause roughness that affects vehicle fuel use, or it may not be recyclable at the end of its life, all of which would not be considered if only the material's production stage is included in the study. Benchmarking studies that include only one or a few life-cycle stages should include a statement regarding uncertainty caused by truncation of life-cycle stages in the documentation of limitations. Similarly, the exclusion of elements of the pavement structure, such as subgrade preparation or shoulders, should be considered with respect to the goal and scope of the study.

All elements should be included in single system attributional studies for pavement structures. In comparative studies where certain elements are exactly the same throughout the analysis period and have no impact on inputs or outcomes, these elements can be excluded and their exclusion should be documented; the results of the analysis, however, will not be comprehensive in terms of total impact, and this should also be documented.

Cutoff criteria are the criteria for excluding unit processes from the analysis (or excluding inputs or outputs from unit processes) when those processes (or inputs or outputs) are not expected to affect decision making. The establishment of cutoff criteria is considered acceptable practice and is usually done to eliminate the effort of creating data inventories for flows that are not impactful. Preliminary inventory data for these processes still must be collected and analyzed to examine the expected impacts to determine whether cutoff criteria have been met. More commentary regarding how to approach this problem in pavement LCA is presented in section 3.3.3.

The cutoff criteria used in a pavement LCA study should be established based on accepted standards such as EN15804 (CEN 2013) or ISO 14044 (discussed in greater detail in section 3.3.3), and the assumptions upon which the cutoff criteria are established should be clearly described in the scoping of the LCA. The effect of the selected cutoff criteria on the outcome of the study should also be assessed and described in the final report as part of the sensitivity analysis (the scoping of which is described later).

Several types of cutoff criteria are used in LCA practice to decide which processes, inputs and outputs are to be included in the assessment. These include mass balance, energy balance and environmental significance. All three of these criteria should be considered for cutoff in pavement LCA. The identification of inputs based on any two or three criteria alone may result in the omission of important inputs (i.e., inputs having significant effects on the third criterion) from the study. For example, some pavement materials make small mass contributions to the pavement but can have large environmental impacts for specific indicators, while other materials with large mass or energy contributions can have large impacts on other processes, such as transportation fuel use (in the case of materials with large mass contributions).

When the study is to be used in developing comparative assertions that are intended for disclosure to the public, the final sensitivity analysis of the inputs and outputs data should include the mass, energy and environmental significance criteria so that all processes and inputs/outputs are included until greater than 95 percent of the contributions to the total of each of the three types of criteria are included in the study (ISO 2006b). This cutoff threshold can be difficult to meet, considering the uncertainty of pavement inventories at this time.

Sensitivity Analysis for System Boundaries

Sensitivity analysis is the use of systematic procedures for estimating the effects of the choices made regarding assumptions, methods and data on the outcome of a study (ISO 2006b). A process and criteria for using the sensitivity analysis to test which processes and inputs and outputs should be included or excluded should be established as part of the scope definition. Application of the cutoff criteria can only be done once the collection of inventory data has begun. As inventory data are collected and impact analysis begins (see chapter 5), the system boundaries may need to be adjusted based on the results of sensitivity analysis and application of the cutoff criteria.

The following elements of the LCA study should be considered for system boundary changes in pavement LCA:

- Functional unit.
- Analysis period.
- Processes and inputs and outputs for individual processes in the life-cycle inventory.
- Life-cycle stages.
- Traffic considerations in the use phase (defined later).
- Future rehabilitation and maintenance treatment types and schedule based on variability of performance and alternative future decisions.
- Fleet composition.
  - Speed distribution.
  - Traffic growth change.
  - Improvement of vehicle technology and emissions standards.
- Allocation methods (defined below and in chapter 5).

3.2.4 Determine Allocation Procedures

Allocation is the partitioning of 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 2006b). ISO recommends that allocation be avoided wherever possible but, where allocation is unavoidable, it is important that the input or output flows be partitioned in a practical way that reflects their actual relationships with the product systems.

There are a number of situations in pavement LCA where allocation is currently needed, including:

- Production of asphalt in a petroleum refinery, where allocation is needed because the processes for producing asphalt also produce other petroleum products.
- Use of supplementary cementitious materials (SCM) in hydraulic cement concrete where the environmental benefits of replacing some of the portland cement in concrete are a result of using an SCM produced in a different process (e.g., fly ash produced in the combustion of coal).
- The use of recycled materials where allocation is needed to account for the upstream processes outside of the pavement system (e.g., asphalt binder from recycled asphalt shingles from waste produced at a shingle factory) and the current pavement processes as well. A similar situation can be applied to any materials coming into pavement from industries that are primarily focused on nonpavement products.

- Allocation of the environmental effects of recycling existing pavement materials into new pavement materials (e.g., the use of recycled asphalt pavement in new pavement), for which benefits and impacts can be attributed in part to both the new material and the original material.

The tasks executed when determining *allocation* procedures as part of the goal and scope definition are:

1. Identify what processes need allocation.
2. Determine allocation approaches for co-products, reuse and recycling.

The main points of the allocation procedures laid out in detail in ISO 14044 (ISO 2006b) are summarized as guidance for pavement LCA practitioners in this document. The general points are:

- The inputs and outputs should be allocated to the different products according to clearly stated procedures that should be documented and explained together with the allocation procedure.
- The sum of the allocated inputs and outputs of a unit process should be equal to the inputs and outputs of the unit process before allocation.
- Whenever several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted to illustrate the consequences of the departure from the selected approach.

Unit processes with inputs or outputs that may be subject to allocation should be identified and documented when establishing which processes are included in the system boundaries.

Chapter 4 provides details regarding specific approaches to allocation.

3.2.5 Select Aggregated Flow, Impact Categories and Impact Category Indicators

Life-cycle impact assessment (LCIA) is the phase of LCA 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 2006b). The purpose of LCIA is to better understand the environmental significance of the *life-cycle inventory* (LCI) by translating environmental flows into environmental impacts that are presented in different impact categories. Simple benchmarking studies will typically not include impact assessment, but will only include evaluation or comparison of flows.

ISO 14044 requires that the LCIA phase include the following mandatory elements:

- Selection of *impact categories, category indicators*, and characterization models. This includes selection of aggregated flow indicators.
- Assignment of LCI results to the selected impact categories (classification).
- Calculation of category indicator results (characterization).

The impact categories, category indicators and calculation methods should be selected in the scoping phase of the LCA. Items to consider when selecting impact categories, indicators and calculation methods as part of the goal and scope definition are:

- The impact categories and indicators should support the goal of the study.
- The impact category and indicator selection should include project- and location-specific considerations.

Guidance regarding specific impact category indicators for pavement LCA in the U.S. is presented in chapter 5.

The recommended steps for selecting impact categories and indicators are:

1. Review the goal to determine whether the full set of impact category indicators is useful for achieving the goal or, if not, which categories and indicators support the decision making needed to achieve the goal and select those for inclusion in the study.
2. Review categories and indicators besides those that directly support the stated goal that might be relevant to the sponsors or other project stakeholders (e.g., those directly involved or those affected at the location) and select them for inclusion in the study. It should be understood that different indicators will often move in opposite directions (beneficial or detrimental) for a given decision, and that different stakeholders may have different priorities regarding indicators.
3. Identify the calculation method for each indicator selected and the data needed to calculate impact category indicators (see chapter 5).
4. Determine whether to conduct normalization and, if so, how normalization (often achieved by weighting the indicators) will be conducted to support the goal of the study and the needs of stakeholders. In accordance with ISO 14044, it is recommended that an LCIA used in comparative assertions that will be disclosed to the public should employ a sufficiently comprehensive set of impact categories; it is further recommended that the comparison should be conducted considering impact categories one by one, rather than by comparing a single summary score calculated by grouping all indicators into one overall indicator.

The future time horizon for which LCI data will need to be collected should reflect the time horizons considered in each impact indicator calculation. Further details are presented in chapter 5.

Impact category indicator results can be normalized, grouped and weighted, but the decision regarding how to handle those indicators needs to be identified in the scoping of the study. Chapter 5 provides details on handling indicators and indicator normalization.

As part of an LCCA, the "time value of money" is usually included in the analysis in the form of a discount rate. The discount rate reduces the present value of costs that occur throughout the analysis period, with greater reductions applied to costs that occur later in the period. The scientific LCA community has not agreed upon an equivalent to the discount rate for emissions or energy use; therefore, emissions should be treated as having equal impact (without discount) throughout the life cycle, except where dynamic characterization factors are available that account for the changing effect of an emission over time (see section 3.3.5 in this chapter for examples).

3.2.6 Define Interpretation Process

Life-cycle *interpretation* is the phase of life-cycle assessment in which the findings of either the inventory analysis or the impact assessment (or both) are evaluated in relation to the defined goal and scope in order to reach conclusions and develop recommendations (ISO 2006b). The process to be used for interpretation should be selected and outlined in the scoping of the LCA study. The interpretation approach should be tied directly to the goals and other aspects of the scope of the study.

The interpretation process to be used and documented in the scoping document should generally follow the sequence of activities shown here (based on ISO 14044):

1. Identify the significant issues.
2. Evaluate the methodology and results for completeness, sensitivity, and consistency.
3. Draw preliminary conclusions and check that these are consistent with the requirements of the goal and scope of the study, especially with regard to data-quality requirements, predefined assumptions and values, methodological and study limitations, and application-oriented requirements.
4. If the conclusions are consistent with the study goal and scope requirements, report them as full conclusions; otherwise return to previous steps 1, 2 or 3, as appropriate.

More information regarding the interpretation process is presented in chapter 6.

3.2.7 Document Assumptions

All assumptions made in the previous six steps of the study goal and scope development process should be documented as a part of the scoping of the LCA study. Assumptions that are anticipated or known to be needed for subsequent phases of the study (i.e., inventory, impact assessment, and interpretation) should also be documented. Documentation should include the reasons for the assumptions and their expected effects on the results, as well as any changes in assumptions made after the scope and goal have been initiated.

Typical assumptions made in the scoping phase can include reasons for truncation of life-cycle stages and other aspects of the functional unit. Assumptions are also often made in pavement LCA studies regarding the relevance of impact category indicators, and the use of only a few indicators.

3.2.8 Document Limitations

The limitations of the study should be documented as a part of the scoping of the LCA study. These should include documentation of the limitations imposed on any of the guidance items discussed in this chapter, as well as any limitations that will be imposed during the subsequent phases of the study (i.e., inventory, impact assessment, and interpretation). The reasons for the limitations and their expected effects on the results should also be documented.

Items that should, as a minimum, specifically be considered when documenting the limitations of the study in the goal and scope document include:

- System boundary and life-cycle stage truncation.
- Data quality and availability for each stage of the life cycle.

- Impact assessment data.
- Data availability for sensitivity analyses.
- Methodological limitations in the LCA or underlying models.

3.2.9 Define Data Requirements

The scoping of the LCA study should describe the requirements for data to be used in the inventory and impact assessment phases in order to be able to answer the questions posed by the goal within the scope of the study. The goal and scope document for the LCA study should identify the types and sources of data needed for each of the processes within the system boundaries of each phase and identify any data limitations. Data can be obtained from primary sources (e.g., measurements at production sites) and secondary sources (e.g., modeling), including both calculated and estimated values.

Items to consider include:

- The need for primary or secondary data.
- The suitability of average data vs individual data measures.
- Sources of data.
- Preliminary sensitivity of results to data sources.

A single product or system attributional analysis to determine the flows and impacts of the product or system will typically use either primary data from the producer of the pavement product or information from multiple producers for a pavement system. Secondary data are typically used to fill in gaps in primary data for composite materials and pavement systems.

A single product or system consequential analysis that considers how flows and impacts will change beyond the system in response to decisions will typically require data for more than just pavement products and systems. Further details are provided in chapter 4.

Data for a project-level analyses should be specific to the project and, where possible, should include primary data from similar recent projects. Data for network-level analysis can be selected to fill a factorial matrix representing the ranges of systems and conditions across the network; alternatively, network-level databases representing the entire network should be used, if available. Data for policy analysis should consider a factorial of pavements and conditions over which the policy will be applied.

More information regarding inventory and impact calculation data is presented in chapters 4 and 5, respectively.

3.2.10 Define Data-Quality Requirements

According to ISO 14044, *data quality* is defined as “characteristics of data that relate to their ability to satisfy stated requirements” (ISO 2006b). Therefore, the data-quality requirements are dependent on the goal of the study and should be identified and documented in the scoping of the LCA study. General considerations for determining data-quality requirements include:

- Relate data-quality needs to the goal of the study, the indicators to be used, and the sensitivity of the different results that will come from the study and their importance in achieving the goal.
- Review project- and location-specific considerations.

Data-quality requirements should specifically address the following items (based on ISO 14044), although the extent to which each of these considerations needs to be documented can be related to their importance to the goal of the study:

- Time-related coverage: age of data and the minimum length of time over which data should be collected.
- Geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study.
- Technology coverage: specific technology or technology mix.
- Data precision: a measure of the variability of the data values (e.g., variance).
- Completeness: percentage of flow that is measured or estimated. Missing data should be explained, shown as a "missing value," or shown with a modeled value with documentation of the modeling in the goal and scope documentation.
- Representative: a qualitative assessment of the degree to which the data set reflects the true population of data.
- Population of interest (i.e., geographical coverage, time period, and technology coverage).
- Consistency: a qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis.
- Reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study.
- Sources of the data.
- Uncertainty of the information (e.g., data, models and assumptions).

Criteria for assessing data quality are presented in chapter 4.

The initial data-quality requirements can be addressed through preliminary sensitivity analysis during the scoping of the LCA. The preliminary sensitivity analysis should consist of evaluation of the impact category indicators and the different possible inventory sources, and the sensitivity of the indicators to the uncertainty of the inventory sources for the different processes to be included in the system boundaries. If the sensitivity analysis indicates inadequate primary data, then secondary data are often sought as a replacement. Similarly, if the preliminary sensitivity analysis indicates that there is little sensitivity of indicators to the quality of certain data elements, then the level of data quality for those elements can be lower.

Figure 3-2 presents a simple flowchart for determining data requirements during the scoping phase of the LCA, illustrating the movement from the goal and functional unit of the study to the indicators, to the data needs, and finally to the data quality to successfully achieve the study goal. More information on data requirements is presented in chapter 4.

Figure 3-2. Example process for determining data requirements (data source: CEN 2013).

3.2.11 Determine Critical Review Process

Decisions concerning the need for and nature of the critical review should be determined during the scoping of the LCA study. The critical review evaluates how the LCA study is conducted and whether it addresses the stated goals. It also evaluates the scientific rigor, the data and the methodologies used throughout the study.

The steps in the critical review determination process are (based on ISO 2006b):

- Determine if critical review is needed.
  - If no, document reasons why critical review is not needed.
  - If yes:
    - Determine the type of critical review needed.
    - Develop and document the scope of the critical review and the mandate given to the reviewers.
    - Determine who will be selected to conduct the review (based on the expertise required) and who will chair the review committee.
    - Determine the process of the critical review, including the stages of review.

A critical review is probably not needed if the study results are to be informally used for internal purposes, such as internal benchmarking for improving efficiency at a pavement materials plant, for internal evaluation of a contractor's construction operations, or for scoping estimates prior to initiating a formal LCA study. Critical review is recommended if the results of the study will be used for important internal decisions or benchmarking, and should be included in the scope of the study if the results are to be communicated externally.

The type and format of the critical review report for the LCA study should be based on the study goal and the intended audience for the study, and should be included in the scoping document.

The critical review process and mandate for the reviewers of the LCA study should be documented in the scoping of the LCA study, including the type of critical review and the qualification of the critical reviewers. In general, the mandate of the reviewers should be to ensure that the LCA study and the methods used to perform it are consistent with ISO 14044, including:

- The methods used to carry out the LCA are scientifically and technically valid.
- The data used are appropriate and reasonable in relation to the goal of the study.
- The interpretations reflect the limitations identified and the goal of the study.
- The study report is transparent and consistent.

As part of the initial scoping, it should be determined whether the reviewers are internal or external to the organization performing the LCA study and whether it is a comparative study. External reviewers should be used for comparative studies that will be published for external uses. External reviewers should also be used for important internal decisions or benchmarking where there is insufficient independence between the reviewers and those who performed the study to obtain a sufficiently unbiased review. Confidentiality agreements with reviewers regarding the content of the LCA should be created as needed.

Details regarding critical review are included in chapter 7.

3.2.12 Determine Reporting Requirements

The results and conclusions of the LCA should be completely and accurately reported without bias to the intended audience. The results, data, methods, assumptions and limitations should be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. The report should also allow the results and interpretation to be used in a manner consistent with the goals of the study.

Some key items to consider in developing the reporting requirements for inclusion in the scoping document:

- Goal and audience.
- Documentation of the scoping of all of the elements discussed in this chapter.
- Documentation of changes in the scoping and assumptions that occurred during execution of the study.
- Transparency documentation.

The report format should follow ISO 14044 Section 6 when the results of the LCA study include impact assessment and will be reported to third parties. More information regarding reporting is included in chapter 8.

3.2.13 Complete Scoping Document for LCA Study

The final step in the preparation of the goal and scope documentation is to complete the document and publish it for internal and critical review.

It is recommended that the outline of the final document for a complete LCA study (as defined in the introduction to this chapter) follow the outline of the guidance given in chapter 8. For less than complete LCA studies, the flowchart for the scoping document should be followed. Reductions in scope can be reported under the same headers, noting that some elements did not apply or were implemented with less rigor or detail. The outline of the scoping document should follow the goal and scope flowchart developed for the study.

The same applies to benchmarking studies where all steps should be included in the scoping, although the system boundaries and life-cycle stages identified in Step 3 will typically be reduced in scope, which will simplify the work in the succeeding steps.

3.3 Commentary

3.3.1 Define Goal

The goal of the LCA is needed to develop the scope for the LCA, and the goal should be adequately defined to ensure that the breadth, depth, and detail of the study are compatible and sufficient to address the stated goal (ISO 2006a).

The goals of LCA studies can be for evaluation of a single product or system or a comparison between two or more products or systems; they can also make use of either attributional or consequential analysis (ISO 2006a).

In an attributional study, the LCA study attempts to answer questions such as “What are the flows and potential environmental impacts of a specific product system” or, in other words, “How are things (i.e., pollutants, resources, and exchanges among processes) flowing within the chosen analysis period for the pavement system of interest?” (ISO 2006a; Harvey et al. 2010). For example, a cradle-to-gate attributional LCA of an aggregate product would examine the exploration and opening of the site, extraction, crushing, sorting, washing, in-mine transport, washing, blending, dust control, erosion control and all other processes to the point at which the product passed through the gate of the mine.

In a consequential study, the LCA study attempts to answer questions such as “What are the environmental consequences of possible (future) changes between alternative product systems?” or “How will flows beyond the pavement system change in response to decisions in the pavement system?” A consequential LCA might ask the question: “What is the effect of a change in specifications for aggregate for use in a pavement application?” The scope of the model would change and would need to include the effects of change in demand for the product from different sources and effects on transportation distances, changes in extraction and processing processes, changes in equipment (including capital costs of producing new equipment), and consideration of which mines would continue producing the given product and which would not, as examples.

The range of possible purposes and goals for an LCA can include, but are not limited to, the following (ISO 2006a):

- Environmental management systems and environmental performance evaluation (e.g., identification of significant environmental aspects of the products and services of an organization).
- Environmental labels and declarations.
- Integration of environmental aspects into product design and development (i.e., design for the environment).
- Inclusion of environmental aspects in product standards.
- Environmental communication.

- Quantification, monitoring, and reporting of entity and project emissions, removals, and validation.
- Verification and certification of specific environmental impact category indicators.

In addition, there are a variety of potential applications in both private and public organizations.

The definition of the goal of the LCA should include consideration of a full range of potential risks to humans and the environment that might be expected from the systems being analyzed and the decisions that the study will support.

3.3.2 Determine Functional Unit

Physical Boundary Definitions and Dimensions of Functional Unit or Declared Unit

For pavement, it is often important to define the physical dimensions used for the pavement structure or material to be typical of pavement construction projects or delivery units of material so that the LCA modeling is of realistic scale for the questions being asked. The functional unit should include items of physical dimensions such as length, width, and number of lanes (in special cases, such as parking spaces, the total area might be more appropriate), the inclusion or exclusion of the shoulders and median. It should also include indicators of the performance of the pavement (e.g., design life) and criteria for performance (e.g., safety, ride quality, traffic levels, load spectrum, speed characteristics, climatic conditions and engineering specifications) (Harvey et al. 2010).

The functional unit used for modeling processes in LCA should have a similar scale to be applicable to the goal of the study and to be representative of its intended application. Normalization to a convenient size for comparison or communication should only occur by normalizing results from an appropriately scaled unit that is consistent with the intended application, performance standard and location. For example, the unit for major highway work should be scaled to match a typical project size, such as “full-scale highway construction,” “city street repair,” or “localized patching,” all of which can later be normalized in terms of a convenient unit for comparison and communication (e.g., lane-mile, yd^2 of pavement surface, etc.). However, defining the functional unit as 1 m^2 (90 yd^2) of a layer of material makes it difficult to get reasonable data for materials production and construction (such as type of the equipment used, or thickness and number of lifts), use, or recycling, or to be able to look at the data or the LCA results and have a sense of reasonableness. It is better to define the functional unit at the application level that defines the service for the end user. Therefore, pavement functional units typically include a full pavement section (often expressed in lane-km or lane-mile that has to function for a period of time.

Some studies normalize physical dimensions of the functional unit after full-scale modeling is done to make it more comprehensible for the audience or to make it easier for comparison (e.g., by taking the lane-width or project-length functional units and then normalizing them into a unit of volume). For example, normalization of the functional unit into volume for the material production stage might be reasonable, but it has no meaning in the use phase, where the lane-mile is much more relevant.

Defined (or declared) units are often used for materials used in pavement construction, such as aggregate, crumb rubber modifier, water-reducing admixtures, water, lime, asphalt binder and cement, which can be used in different quantities in a number of different pavement materials prepared using different processes and having different functional requirements. They may have some properties which may contribute to the final functional properties of the composite materials or works they are used in, but they do not completely define the functionality of the final material or work they are used in. It is recommended that declared units be in terms of the commonly used defining unit type (i.e., mass, volume, area or length) commonly used for pavement design, procurement and construction for their product family. (CEN 2013)

Analysis Period

The time horizon or the analysis period refers to the duration in which the inputs and outputs associated with the functional unit are inventoried; pavements in particular impose major challenges because initial construction and future maintenance and rehabilitation events often have different functional design lives (Harvey et al. 2010).

To make a reliable statement about the impacts of a product/service or to make a fair comparison between alternative systems that offer competing products/service, the functional unit needs to define an appropriate time horizon for analysis. Typically for pavements, the intention of setting the analysis period is similar to that used for LCCA: capture the performance of the initial product or service and its effect through the life of at least the next subsequent major rehabilitation treatment, and preferably through the lives of following rehabilitation treatments or the next full reconstruction.

The US DOT (2003) provides the following general guidance for selecting LCCA analysis periods:

> *As a rule of thumb, the analysis period should be long enough to incorporate all, or a significant portion, of each alternative's life cycle, including at least one major rehabilitation activity for each alternative (typically a period of 30 to 40 years for pavements, but longer for bridges). In some cases, an analysis period long enough to capture the life cycle of one alternative may require that a shorter lived alternative be repeated during that period.*

The FHWA (1998) provides this guidance regarding LCCA; it is also applicable to LCA:

> *LCCA analysis period should be sufficiently long to reflect long-term cost differences associated with reasonable design strategies. The analysis period should generally always be longer than the pavement design period, except in the case of extremely long-lived pavements. As a rule of thumb, the analysis period should be long enough to incorporate at least one rehabilitation activity. The FHWA's September 1996 Final LCCA Policy statement recommends an analysis period of at least 35 years for all pavement projects, including new or total reconstruction projects as well as rehabilitation, restoration, and resurfacing projects.*
>
> *At times, shorter analysis periods may be appropriate, particularly when pavement design alternatives are developed to buy time (say 10 years) until total reconstruction. It may be appropriate to deviate from the recommended minimum 35-year analysis period when slightly shorter periods could simplify salvage value computations. For example, if all alternative strategies would reach terminal serviceability at year 32, then a 32-year analysis would be quite appropriate.*

The lack of specific standards for pavement also means that a range of functional units and analysis periods have been used for pavement. An extensive literature review of available LCA studies on pavements shows a wide range between functional units and time horizons considered by the researchers, which most likely reflects different goals and different systems being analyzed; these are presented in table 3-2. The analysis periods indicate that there is a wide range of possible analysis periods for pavements, reflecting the wide range of pavement lives (from 5 to 100 years). This makes the selection of an appropriate analysis period a balancing act between reducing the uncertainty regarding the ability to predict future information (which calls for shorter analysis periods) and the need to consider the ramifications of a given pavement decision on future maintenance, rehabilitation and reconstruction decisions (which calls for longer analysis periods).

Table 3-2. Example functional and declared units and analysis periods for LCA.

LCA Element	Examples From Literature
Functional Unit	Rehabilitation project on interstate freeway Maintenance of several miles of city street One parking facility One year of pavement maintenance and rehabilitation on entire state highway network Normalized functional or declared units 1 km or mile, or project length 1 lane-km or lane-mile, or any number of lanes or lengths 1 m^2 or ft^2 of pavement material, or unit area, or number, or project surface area 1 m^3 or yd^3 of pavement material, or unit of volume, or number, or project volume 1 ton of pavement material, such as asphalt, or scrap tire 1 hour of mixing plant output Small network of 8 road segments with 2 lanes
Analysis Period	100, 50, 40, 34, 30, 25, 20, 18, 10, 5 years Material production and construction stages only

Illustration of recommended guidance for selecting analysis periods for comparison analyses is given by the following examples.

- When comparing two new pavements or pavement reconstructions (see figure 3-3):
  - The analysis period should be the time through the life of the first major rehabilitation or reconstruction of the longest lived alternative.
  - The impacts of the shorter lived alternative and all subsequent treatments up to the end of the analysis period should be included, truncating the final included treatment at the end of the analysis period.
- When comparing a new pavement or reconstruction to a rehabilitation (see figure 3-4):
  - The analysis period should be the time through the life of at least the first subsequent major rehabilitation or reconstruction (typically the reconstruction) of the longest lived alternative.

  - The impacts of the shorter lived alternative and all subsequent treatments up to the end of the analysis period should be included, truncating at the end of the analysis period.
- When comparing two rehabilitation or maintenance treatments (see figure 3-5):
  - The minimum analysis period should be the time through the life of at least the next subsequent rehabilitation treatment of the longest lived alternative if comparing rehabilitation treatments, and through the life of at least the next subsequent maintenance treatment of the longest lived alternative if comparing two maintenance treatments.
  - The impacts of the shorter lived alternative and all subsequent treatments up to the end of the analysis period should be included, truncating at the end of the analysis period.
- When comparing a rehabilitation treatment to a maintenance treatment (see figure 3-6):
  - The analysis period should be the time through the life of at least the first subsequent major rehabilitation or reconstruction (typically the rehabilitation) of the longest lived alternative.
  - The impacts of the shorter lived alternative and all subsequent treatments up to the end of the analysis period should be included, truncating at the end of the analysis period.

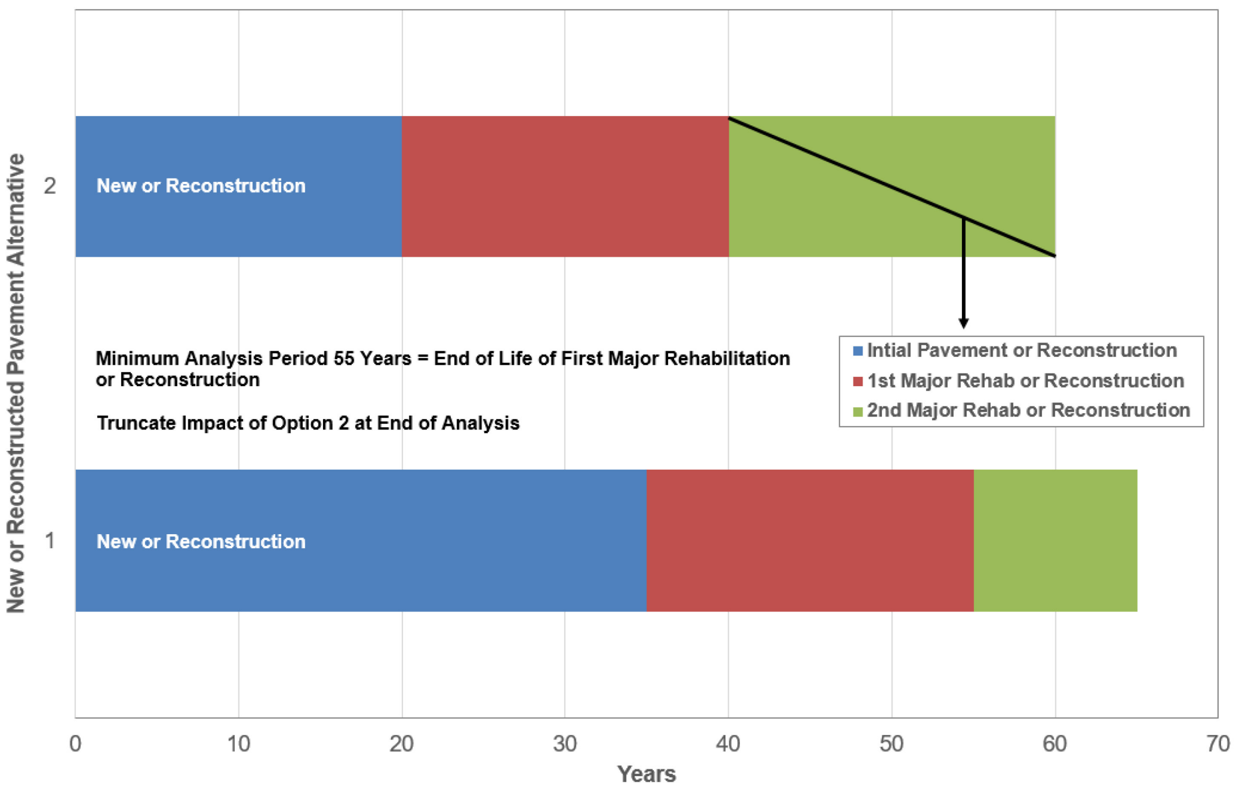

Figure 3-3. Minimum analysis period recommendation for comparing two new pavement or reconstruction alternatives (note: the arrow indicates truncation of the 2nd rehabilitation for the shorter lived alternative at the end of the life of the first major rehabilitation or reconstruction of the longer lived alternative at 55 years).

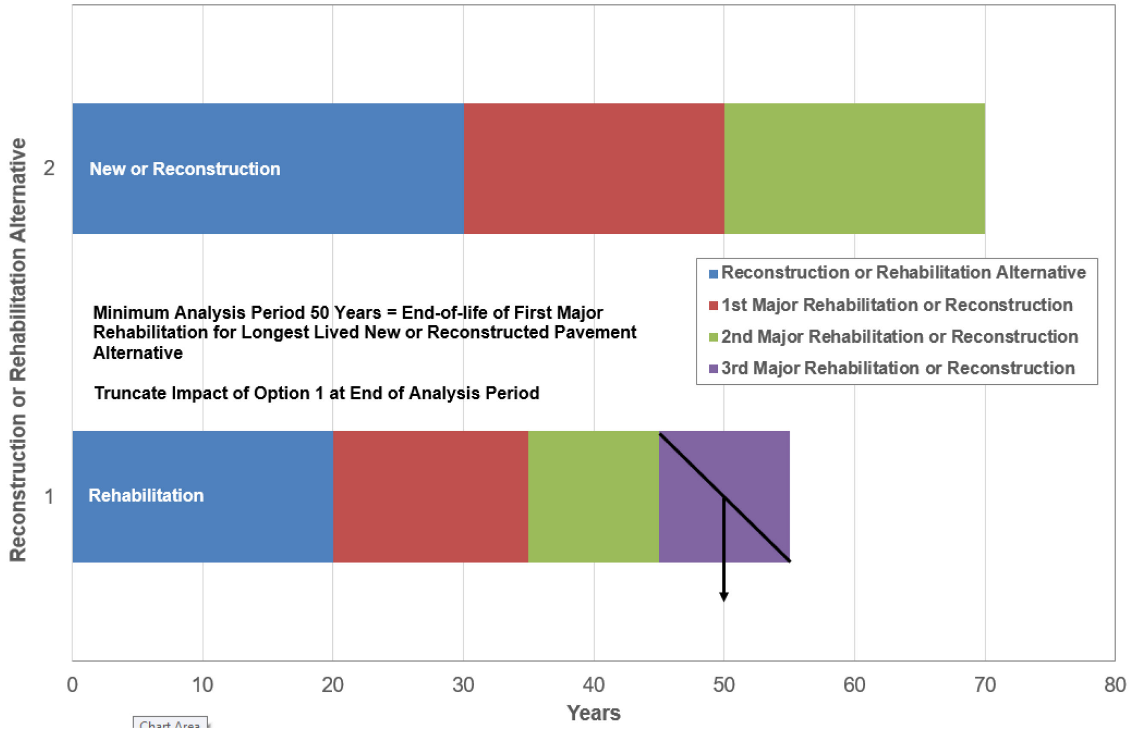

Figure 3-4. Minimum analysis period recommendation for comparing a new pavement or reconstruction alternative to a rehabilitation alternative (note: the arrow indicates truncation after the life of the first major rehabilitation for the longest lived alternative at 50 years).

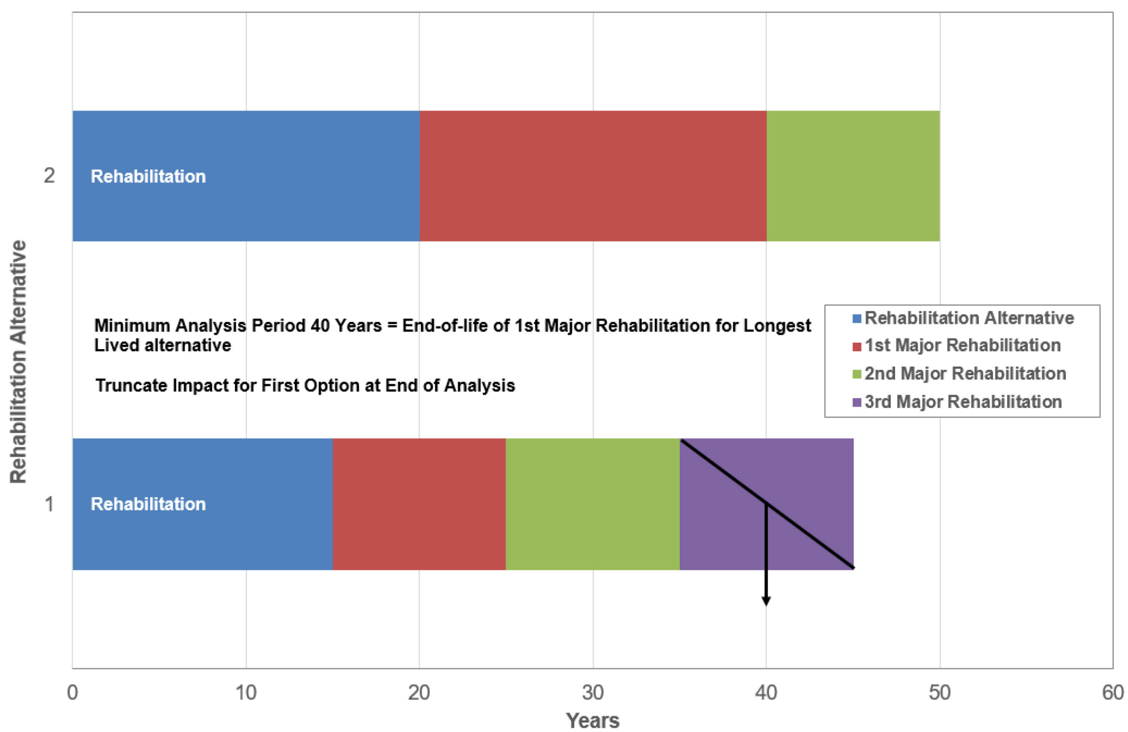

Figure 3-5. Minimum analysis period recommendation for comparing two new rehabilitation or maintenance alternatives (note: the arrow indicates truncation after the life of the first subsequent major rehabilitation for the longest lived alternative at 40 years).

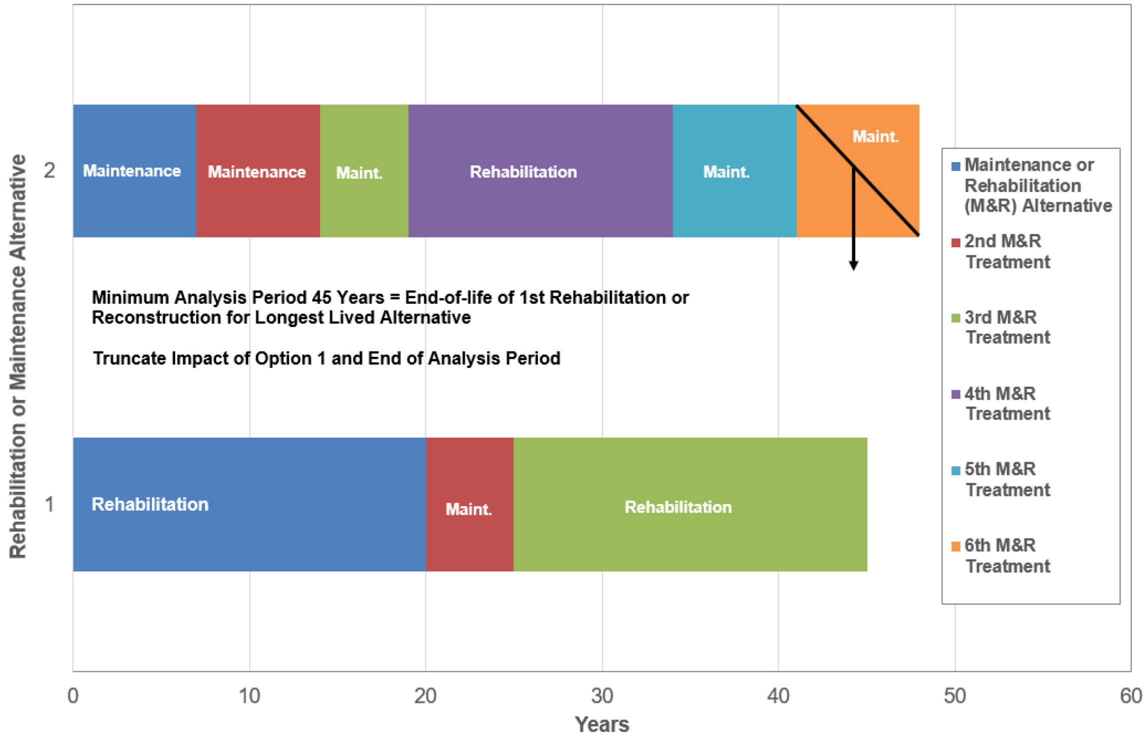

Figure 3-6. Minimum analysis period recommendation for comparing a rehabilitation treatment and a maintenance treatment (note: the arrow indicates truncation after the life of the first subsequent major rehabilitation for the longest lived alternative at 45 years).

After selection of the appropriate analysis period following the guidance given above, the total results over the analysis period from comparison studies can be divided by the number of years in the analysis period to provide an indication of average annual results, as was done in Wang et al. (2012), for example.

Where there is a large degree of uncertainty in future treatments, for example where one alternative has a much shorter initial life than the longest lived alternative and a large number of future treatments must be assumed, then sensitivity analysis should be included regarding future treatments.

> *It is important to capture all costs that differ among the alternatives being compared. Where uncertainty associated with future costs is identified, the analyst should assess its potential impact on the alternative using appropriate risk analysis methods.*

The time horizon might not always be in years. For example, a motor vehicle functional unit could be defined as the miles driven, years of use, or both. Similarly, pavement time horizons might be expressed in terms of traffic repetitions, regardless of the time period over which those occur (Kendall and Santero 2010).

3.3.3 Define System Boundaries and Pavement Life-Cycle Stages

The following list represents a generic unit process (ISO 2006c):

- Inputs.
  - Raw (intermediate) material.
  - Ancillary material.
  - Energy.
- Outputs.
  - Products.
    - Intermediate product.
    - Co-product.
  - Emission/waste.
    - Emissions to Air.
    - Emissions to Water.
    - Emissions to Land.
    - Waste for treatment.

Figure 3-7 (Harvey et al. 2011) shows a sample list of the elements of the processes in each stage that can be included in system boundaries of the LCA study, depending on the goal and the functional unit, although there is differing availability of calibrated models and approaches for each process.

If the LCA is applied to a preservation, maintenance, or rehabilitation activity where the base/subgrade/drainage remain unchanged and are not used for comparison and are not part of the decision, then those aspects of the structural design can be left outside the system boundary. Similar principles apply for the exclusion of parts of the pavement system, depending on the goal of the study.

The following processes should be considered for inclusion in the stages shown in figure 3-7, depending upon the goal of the study (Harvey et al. 2011):

- Material production stage:
  - Raw or recycled material acquisition.
  - Transport of materials to the processing unit.
  - All the processes conducted on the materials in the plant.
  - Various types of energy should be considered separately (see chapter 5 for more guidance).
- Construction and maintenance and rehabilitation stage:
  - Transport of equipment to the site.
  - Transport of materials from the processing unit to site and, in the case of demolition, transport of materials from the site to its final disposition (e.g., recycling plant or landfill).
  - Manufacturing and investments solely related to the construction project under study.

  - Water use.
  - Electricity use for lighting during construction.
  - Traffic congestion (and extra fuel burned as a result) due to construction activity.
  - Temporary infrastructure built for the construction stage.
- Use phase:
  - Additional fuel consumption by the traffic due to initial condition of the pavement and considering changes in pavement condition over the analysis period. The pavement condition includes:
    - Roughness (some calibrated models are available).
    - Texture (some calibrated models are available).
    - Structural response (models are available, calibration is underway).
  - Effects of ambient temperature changes in urban areas caused by the pavement (modeling is currently being developed).
  - Electricity used during the use phase for lighting pavements if reflectance is considered a function of the pavement (some information is available and some agencies consider pavement reflectance in designing lighting requirements).
  - Leachate of pollutants into underground water through the pavement during rainfall.
  - Storm water runoff (models are available, but are not yet typically applied to pavement LCA).
- End-of-life stage, considering the fate of the pavement that can include recycling and hauling to a landfill:
  - Reuse and recycling.
  - Emissions and fuel use from demolition and hauling of debris.
  - Leachate from landfilling (availability of models is uncertain).
  - Leachate from formerly bound materials now being used as unbound base (no models are currently available).

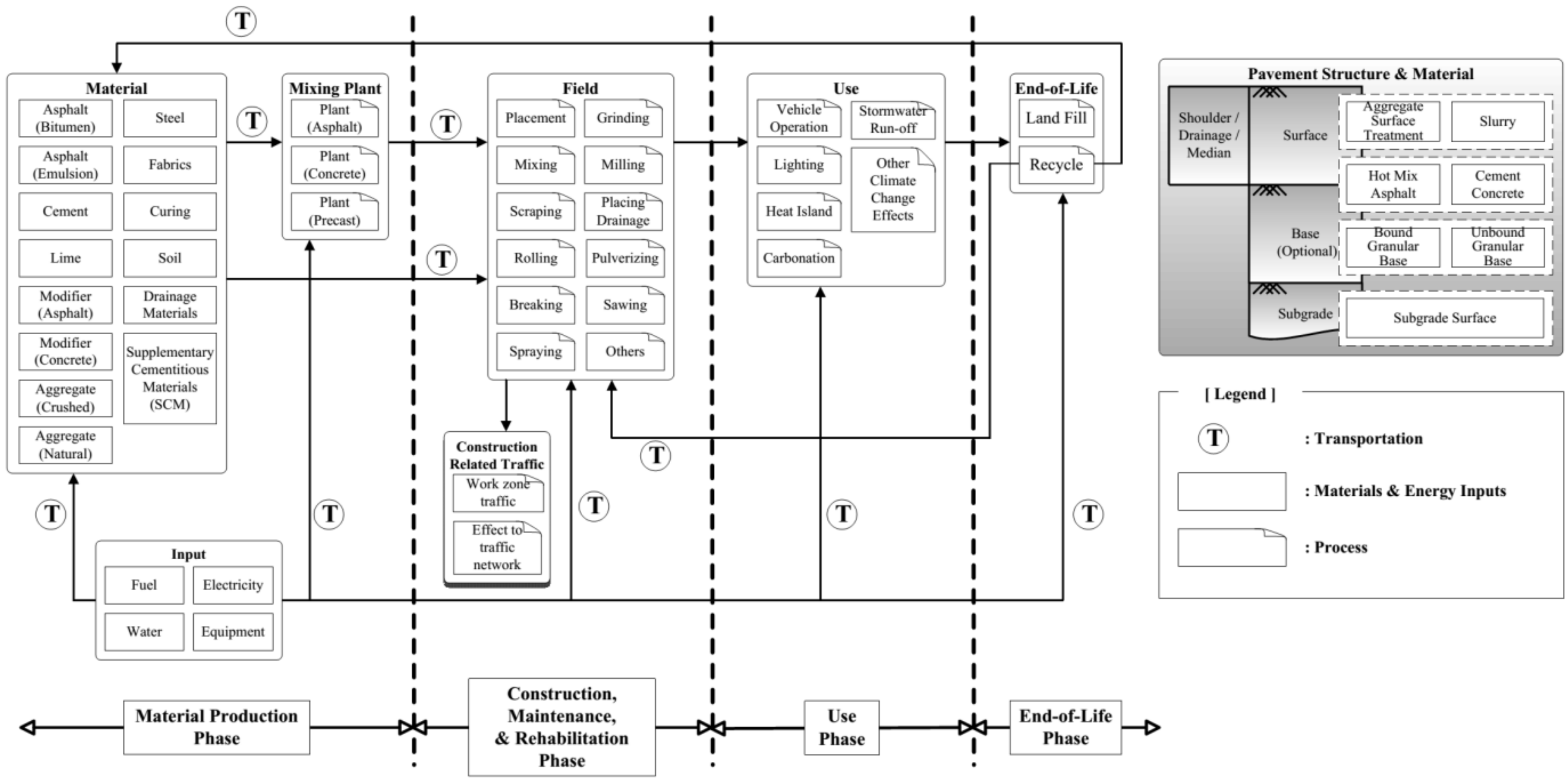

Figure 3-7. UCPRC LCA framework showing major life-cycle stages of a pavement (Harvey et al. 2011).

If the goal does not require consideration of the full life cycle, LCA techniques can still be used for studies that have other scope definitions, such as (ISO 2006a):

- Cradle-to-gate studies, which includes materials extraction and processing.
- Gate-to-gate studies, which considers processing of a material in a plant.
- Cradle-to-gate with options (which includes the product stage and selected further life-cycle stages).
- Specific parts of the life cycle (e.g., waste management, components of a product, and the use phase).

For pavement LCA, the purpose might be to characterize a category of projects with subsequent policy- or decision-making implications, or it might be project specific, where information for decision making is sought for a specific project. If the goal of the LCA is a framework that can be used across multiple projects, information reflecting average temporal and spatial variability may be needed. Conversely, in project-specific LCAs, site-specific and project-specific information should be used (when available) to develop local results. This type of resolution will be particularly important in the impact assessment phase.

Cutoff criteria for mass and environmental impact for pavement can often be established in the regulations for reporting limits for different outputs applicable to the functional unit. This can aid in data collection, since it is often difficult to find data for regulated items if they are occurring below the reporting limit. A maximum cumulative indicator effect of five percent for all cutoff flows is the recommended threshold for each of the criteria (mass balance, energy balance, and environmental aggregated flows and impacts). The following are recommendations for appropriate mass, energy and environmental impact criteria (ISO 2006b):

- **Mass Impact Criterion**. Criterion require the inclusion of all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modelled.
- **Energy Impact Criterion**. Similarly to the mass impact criterion, energy impact criterion require the inclusion of those inputs that cumulatively contribute more than a defined percentage of the product system's energy inputs. The various forms of energy (i.e., primary, secondary, renewable, nonrenewable, used as fuel and stored in a material) can be considered for cutoff and truncation, although ISO and CEN standards do not differentiate what energy types to consider. In general, primary energy demand is used as the energy cutoff criterion.
- **Environmental Significance.** Decisions on cutoff criteria should be made to include inputs that contribute more than an additional defined percentage of the estimated quantity of the product system components that are specifically selected because of their environmental relevance.

While data inventories are available for many pavement materials, they are not available for a number of materials used in small quantities that potentially have large energy and environmental contributions. This occurs particularly when proprietary additives, admixtures and modifiers are used in asphalt and concrete mixtures to improve their properties. In many cases the chemical components and processes used to make these materials are proprietary and are not disclosed, making it difficult to create a new inventory when one does not exist. At this time the following are possible approaches, suggested in order from short-term to long-term recommendations:

1. Work with the product manufacturer:
    a. Ask the manufacturer of the material for an EPD.
    b. Ask the manufacturer for a list of active and inert materials included in the product and for an estimate of their relative quantities.
    c. If this information is not made available and further steps are not feasible, then the LCA study must document this gap in the LCI and LCIA. Any indication of potential effects on the outcome of the study from available information regarding the product, such as the identification of at least some of the ingredients or ingredient family types, should be discussed in the limitations of the study.
2. Work with a chemical or LCA consultant to identify materials in the product and develop inventory and indicator information for the ingredients in the product or product family. This approach can be facilitated through the use of technology such as Fourier Transform Infrared Spectroscopy (FTIR), which can identify many known chemicals and are increasingly available in pavement materials laboratories.
3. Require EPDs for all materials used in pavements.

3.3.4 Determine Allocation Procedures

The ISO standards for LCA prescribe a hierarchical preference for how to assign, or *allocate*, environmental flows that occur in the modeling of the LCA. These allocations must be assigned whenever a production system boundary is crossed. For example, when one pavement life cycle ends and another begins, allocation must be utilized when assigning environmental impact to the material that is recycled from the pavement (i.e., how much of the environmental impact of the material stays with the original pavement and how much is transferred with the recycled material to the new pavement).

A general consensus among LCA practitioners and those involved in evaluating products and systems is that allocation rules should be set up to (based on presentations and discussions at the 2012 Nantes conference on LCA for civil infrastructure [see, for example Huang, Spray, and Parry 2013] and the 2014 pavement LCA symposium held in California [see, for example, Geyer 2014]):

- Prevent double counting of credits or the omission of important items.
- Provide fairness between industries by reflecting as closely as possible what is actually happening.
- Be transparent so that all parties can understand how allocation is applied and how it influences the results.

Definitions of different materials and processes requiring allocation in pavement LCA are presented in chapter 4, along with a discussion of specific approaches for allocation.

Double counting is not allowed in the ISO standards, and presents a major problem in the transparency and use of LCA studies to effectively determine environmental burdens. This problem is directly applicable in pavement LCA studies, particularly for two cases:

- Case 1, when the pavement LCA uses a waste product (which means it has no economic value) from a nonpavement industry and assumes that all of the environmental burden of producing that waste lies with its upstream producer, while at the same time the producer of that waste is reporting reduced environmental burden in producing the waste because of the downstream recycling in pavement. Some examples of where this can occur include:
  - The use of construction demolition waste (CDW) from buildings for granular base and subbase material.
  - The use of fly ash from the burning of coal to reduce the use of cement in concrete.
  - The use of blast furnace slag to reduce the use of cement and aggregate.
  - The use of recycled tires in asphalt binders and other pavement applications.
- Case 2, when a pavement LCA for a project uses recycled pavement materials from previous projects. Some examples of where this can occur include the use of RAP in new asphalt mixes and the use of RCA in granular bases, new asphalt mixes, or new concrete mixes.

Currently, there is no authority in the U.S. or any other part of the world that can determine the appropriate approach when there is double counting due to conflicting assumptions in LCA studies in different industries or between different pavement LCA studies. The approach to be used must be selected and documented, and it is recommended that any known conflicts with other LCA studies for materials being used in the LCA study should be clearly identified in the *Assumptions* section of the study.

Because alternative allocation approaches are often applicable to pavement processes, allocation should typically be included in the sensitivity analysis for pavement LCA studies, as is discussed in chapter 4. The sensitivity analysis for allocation methods should be documented in the scoping of the LCA study.

3.3.5 Select Aggregated Flow, Impact Categories and Impact Category Indicators

Pavement LCA studies select indicators, including selected aggregated flows from LCI and impact category indicators for selected impact categories that are most relevant to the specific project goal and scope. These indicators can range from those that narrowly focus on energy and GHG to a complete set of impact categories.

The most frequently used impact categories are GHG alone or GHG and energy used together. These two impact categories tend to be correlated, since combustion of fossil fuels is often the largest source of GHGs. Focusing on only these two categories ignores a number of important environmental burdens that affect people, ecosystems and the depletion of material resources. Work by Laurent, Olsen, and Hauschild (2012) and others indicates that many impact categories have little or no correlation with global warming or energy use. In general, impact category indicators that are not tied to the burning of carbon-based fuels are less likely to be tied to those two commonly selected indicators.

Pavement LCA studies should include all aggregated flows and impact category indicators that are relevant to the goal of the study. In addition, there may be large differences in the values or importance of impact category indicators for different regions of the country. Some indicators may be of much greater or lesser importance to different regions, such as fine particulate emissions in regions with good air quality compared to regions that are deemed Clean Air Act nonattainment zones. The appropriate categories to meet the goal of the pavement LCA study should be included in the selection of the aggregated flows and impact categories, and it should not be assumed that energy use and global warming potential (GWP) are surrogate measures of other impact categories. The selection of environmental indicators should include consideration of the full range of potential risks to humans and the environment that might be expected from the systems being analyzed and the decisions that the study will support.

Impact indicators occurring during the analysis period that include a time component in the impact calculation model should consider time as prescribed by the model.

Nonrenewable energy use and other nonrenewable resource consumption indicators are defined by whether they are replaced by nature within 100 years. For example, energy from biomass is generally considered renewable within 100 years, while fossil fuels are not.

Wherever possible, it is recommended that impacts should be calculated based on regional values rather than national or international averages. While global warming and ozone depletion have global impacts that are independent of the emission site, the other impacts listed above often have regional and local impacts with strong dependency on emission site (Rosenbaum 2014). It should be noted that some of the TRACI impact categories are calculated as a national "average" impact, while others include more sophisticated location-specific approaches and location-specific characterization factors, as well as U.S. average values for use when the location of the inventory data is not available (Bare 2002). Chapter 4 provides a discussion regarding normalization techniques that can include regional differences in the impact categories.

The most common impact assessment methods found in the pavement LCA literature include CML, IPCC (Intergovernmental Panel on Climate Change), Eco-indicator, and TRACI (from EPA). However, most pavement LCI studies found in the literature did not follow these impact assessment methods and, instead, used their own aggregation and presentation methods that include a summation of impacts, like solid waste or individual emissions, rather than impact assessment.

Current LCA methods treat emissions identically regardless of when they occur in a product's life cycle, which can lead to a miscalculation of their true effects on the various systems they impact. Dynamic impact calculations can account for processes that have higher levels of emissions that occur early in the impact calculation analysis period and, therefore, have a heavier impact than an assumption of equal emissions over the analysis period would indicate because of the greater exposure time for the system being affected. This is often true of pavements where the initial materials extraction and processing period produces intense emissions over a short duration at the beginning of the analysis period. Further reading regarding dynamic impact calculation can be found in several of the references for this chapter (i.e., Pehnt 2006; Björk and Rasmuson 2002; Kendall, Chang, and Sharpe 2009; Levasseur et al. 2010; and Kendall 2012).

3.3.6 Define Interpretation Process

Comparisons between products should be interpreted on an impact category by impact category basis, and not based on averaging or other calculations of summary statistics across impact categories. Recommendations should be based on the final conclusions of the study and should reflect the reasonable consequence of the conclusions. If called for by the goal and scope of the study, specific recommendations to decision makers should be explained. Decisions regarding the approaches used for interpretation should be included in the scoping document.

3.3.7 Document Assumptions

The assumptions made for the LCA study, and any limitations on the full performance of a complete LCA will affect the outcome of the study and the answers to the questions posed by the goal of the study. Assumptions are often made in order to complete many of the scope elements, but the significance of the assumptions made depends in large part on whether they change the conclusions. Testing of assumptions with sensitivity studies and critical review are essential elements of LCA, and those assumptions that are found to affect conclusions and recommendations should receive additional attention (where possible) to reduce their uncertainty.

3.3.8 Document Limitations

Limitations on different activities in the LCA in the inventory, impact assessment and interpretation phases are often imposed to reduce the cost and time necessary to complete the study, or because of other limitations on resources, such as scarcity or uncertainty of data. Examples for pavement LCA include limits on the extent of the life cycle in the study, gaps and uncertainties in data, the use of secondary data (as opposed to recent primary data) for processes that may have regional or temporal changes, variability in processes (particularly when deterministic values are used), and lack of regional impact indicator calculations for impact categories that are sensitive to regional differences (such as emissions affecting air quality).

3.3.9 Define Data Requirements

European Standard EN 15804 recommends that, as a general rule, specific data derived from specific production processes or average data derived from specific production processes should be the first choice. In addition, the following requirements are recommended:

- Representative average data should be used when calculating indicators for an average product or process.
- An LCA describing a specific product should be calculated using specific data for at least the processes that are germane to the goal of the study or to the product being assessed in an EPD. Generic data may be used for the processes that are not essential to the question being asked, or that the producer or operator cannot influence for a product or operation (e.g., processes dealing with the production of input commodities, often referred to as upstream data). Suitable data types are by process are summarized below:
  - Upstream processes: generic data.
  - Processes essential to achieving goal of study: specific data.
  - Processes over which manufacturer has control for an EPD: specific data.
  - Downstream processes: generic data.
- Documentation of technological, geographical and time related representativeness for generic data should be provided in the project report.

Moreover, in determining data requirements, both regional applicability and temporal applicability to the goal and functional unit of the study should be considered and appropriate technologies that would be used during the life cycle of the pavement should be considered in selecting data sources.

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CHAPTER 4. LIFE-CYCLE INVENTORY ANALYSIS

4.0 Introduction

4.0.1 Background

The life-cycle inventory (LCI) analysis is the second phase of an LCA, characterized by collecting and processing the data necessary to satisfy the goal and scope. ISO 14040 defines LCI as "the phase of life-cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 2006a). In the LCI phase, all relevant data for some or all of the life-cycle stages (see figure 4-1) should be collected and analyzed in a manner consistent with the methods, rules, and assumptions specified in the goal and scope of the study. These include the unit processes, cutoff criteria, data types and sources, data-quality requirements, and procedures used to address any missing data. The process is iterative in that new data requirements and limitations may be identified as data are collected and more is learned about the system. This may trigger a change in the data-collection procedures to meet the study goals, or may even necessitate a re-examination of the goal and scope of the study. The results from the LCI phase form the basis for the subsequent life-cycle impact assessment phase.

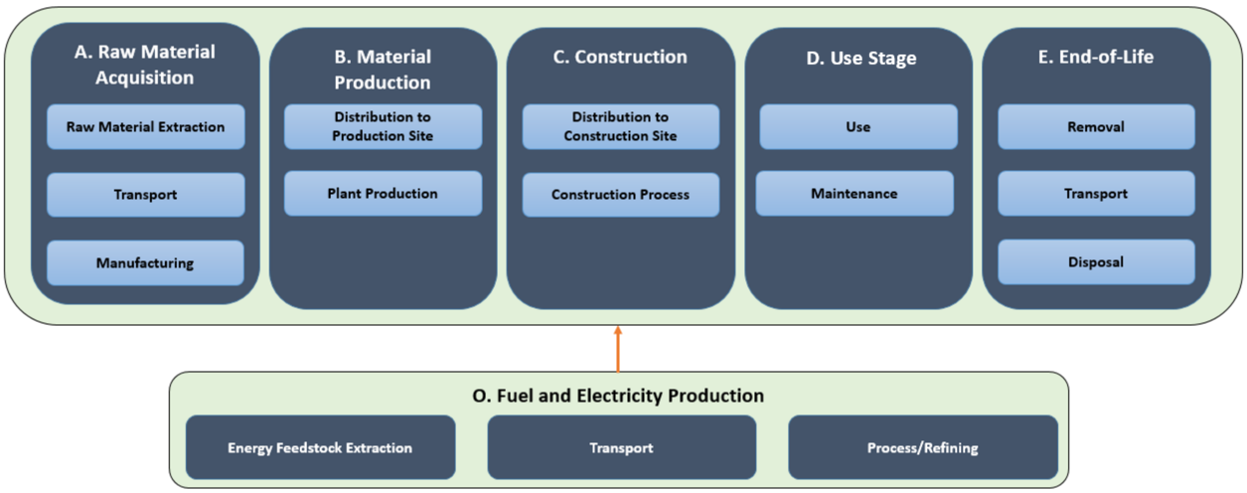


Figure 4-1. Pavement life-cycle stages and a partial list of major aggregated processes that may be included in various pavement LCA applications.

Inventory data collection is applied for all processes included in the system boundary. The system boundary is defined in ISO 14044 as the "set of criteria specifying which unit processes are part of a product system" (ISO 2006b). According to ISO 14044, a unit process is the "smallest element considered in the life-cycle inventory analysis for which input and output data are quantified" (ISO 2006b). Multiple unit processes can be grouped together to form aggregated unit processes representing complex manufacturing processes. The LCI analysis covers all units or aggregated unit processes that fall within the system boundaries that are established during the goal and scope phase. Unit processes and associated inventory data can be considered the building blocks of any LCA, as they describe and characterize both input and output flows from the environment and products. Inputs considered include material or energy flows that enter a unit process (such as raw materials, energy and water use), while outputs considered are products, co-products, material, or energy flows that leave the unit process (such as solid wastes, atmospheric emissions, waterborne emissions, and emissions to soil). An example of an aggregated unit process and typical inputs and outputs in coal mining is shown in figure 4-2.

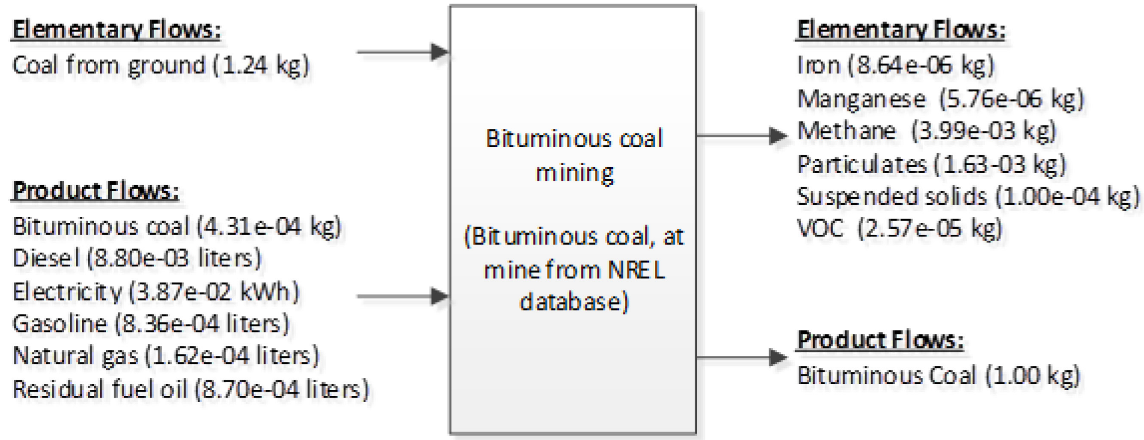


Figure 4-2. An example unit process for coal mining with typical inputs and outputs (NREL 2015).

4.0.2 Inventory Data

The LCI phase involves inventory data collection and modeling of all unit processes within the system boundaries in a pavement LCA such as production and hauling of aggregates, asphalt-binder production and storage, asphalt mixture production, cement manufacturing, concrete production, and various other construction activities. Data types and sources selected for an LCA depend on the goal and scope of the study. Such data may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, the data used for an LCA may include a mixture of measured, calculated, and estimated data.

The inventory data collected are generally classified into two groups: *primary* (also known as specific) data and *secondary* (also known as generic) data. Primary data refer to data collected from specific processes to model the life cycle, and these represent the production and construction of the studied product. Primary data for EPDs are controlled by the owner of the EPD. The collection of primary data is further defined with step-by-step procedures in the guidance section.

Secondary data are often obtained from existing commercially or publicly available databases and literature (e.g., Ecoinvent [EarthShift 2013]

Primary and Secondary LCI Data

Primary Data: *Primary data refer to data collected from specific processes to model a product's life cycle. These data best represent the production stream of the studied product since it is obtained using data collected specific to the process.*

Example: Direct emission or activity data in a specific cement plant producing raw materials for a specific type of concrete mixture used in a pavement LCA.

Secondary Data: *Secondary data are collected using a proxy process that is assumed to be similar to the one being studied, or they may represent industry averages or distributions.*

Example: Average process-activity data or direct emissions (energy usage and production) collected from all dry process kiln cement plants and reported as average by cement associations. Energy consumption and emissions from hauling trucks obtained from EPA software (MOVES) is another example of secondary data.

and GaBi [Baitz et al. 2013]). Examples of secondary data include industry average inventory data for generic products and services, such as material resources, energy, transport and waste processes, or scenarios for the use stage and end of life. For EPDs, secondary data are not directly controlled by the owner of the EPD and may be characterized as upstream data (data from the supply chain) or downstream data (typically for the life-cycle stages after the manufacturing or construction).

Secondary data can have the same quality as primary data, but care should be given to review the data quality and to justify whether they meet the data-quality requirements for satisfying the goal and scope. It is important to review the data quality for possible inconsistencies that frequently occur between different data sources, which may be the result of inconsistent system boundaries, different geographic coverage, completeness, etc.

4.1 Flow of Work for Inventory Analysis

Inventory analysis is composed of collecting a blend of primary and secondary data, depending on the goals and intended application of the LCA. The flow of work for inventory analysis is shown in figure 4-3. This includes key procedures for inventory analysis (which correspond to the chapter organization) and is adopted from ISO 14040 and 14044 requirements, in addition to the European Standard Norms for sustainability of construction works.

The flow of work for inventory analysis for conducting an LCA consists of eleven steps as outlined below and discussed in greater detail in the rest of the chapter.

1. **Prepare for Data Collection.** Includes development of data-collection strategy and formats, drawing of flow diagrams for major processes, and identification of data types and sources. Preparation should start with checking out data and quality requirements, data assumptions, and other information related to inventory data defined in the goal and scope document.
2. **Collect Initial Data for the Material-Production Stage.** Uses primary or secondary data sources. This is the step where input and output flows for major pavement materials and production processes are collected from the identified sources. If the intended goal of the study requires data collection for other life-cycle stages, proceed to step 3; otherwise, proceed to step 4.
3. **Collect Initial Data and Develop Models for Other Life-Cycle Stages**. Includes construction, maintenance and rehabilitation, use, and end-of-life stages. Unlike the materials-production stage, models directly relating the pavement's functional and structural characteristics to the environmental impacts will need to be utilized in the use stage to develop output flows.

Figure 4-3. Flow of work and key procedures for inventory analysis recommended for each unit process (data source: ISO 14044 [ISO 2006b]).

4. **Complete Initial Data Collection.** Uses models and other data sources. This step is needed when the data collected in steps 2 and 3 are not sufficient to characterize impact categories identified in the goal and scope phase. Data completion can be done using data from other sources or using emission factors and other types of data models (e.g., water use models, land use models, energy use models, fuel use models, etc.) that are available from the literature and commercial LCI databases. When directly measured flows are unavailable or insufficient, emission factors and other models can be used to complete the missing released emissions or resource uses from a specific unit process or aggregated unit processes. According to the EPA AP-42 definition, "an emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant" (EPA 1995). Emission factors can be used to convert activity data (raw material, total production, or energy consumed) to released emissions.

5. **Validate Data.** This includes checking that inventory inputs and outputs are within reasonable ranges (e.g., completeness of mass [mass balance], energy [energy balance] and environmental relevance, or comparative analyses of inventory items against other sources).
6. **Aggregate Data.** Individual unit processes representing the supply chains and production streams of major pavement materials are aggregated where relevant. The unit processes to be included in the data aggregation are defined by flow diagrams and system boundaries for each material.
7. **Translate Data to Unit Processes and Functional Unit.** Inventory input and outputs can be expressed per unit mass or volume of production or per reference flow (measure of the outputs required to fulfill the function expressed by the functional unit). Then, input and output flows associated with a single unit process or aggregated unit processes (e.g., asphalt mixture production, cement manufacturing, concrete mixture production, etc.) are defined per the functional unit.
8. **Perform Allocation.** Inventory input and outputs are allocated to the products or system studied following the allocation methods identified in the scoping phase where applicable. Allocation rules should be applied for the following situations:
   - Manufacturing processes with co-products (e.g., oil refineries and asphalt-binder production processes).
   - Processes or systems used by multiple products (e.g., transport of multiple goods and raw materials).
   - Reuse and recycling of pavements at the end of their life.
   - Multi-input situations (e.g., landfill, waste treatment).
9. **Apply Decision Rules and Refine System Boundaries.** Inputs and outputs to be included or excluded in the final inventory database are determined after applying cutoff rules identified in the scoping phase. Following any inclusion or exclusion from the initial collected data, system boundaries should be refined and steps 1 to 9 should be repeated for the unit processes affected by any changes.
10. **Assess Data Quality.** The quality of collected data is checked for consistency and compatibility with the goal and scope of the study.
11. **Prepare Documentation.** Inventory inputs and outputs are finalized and documented along with data sources, major limitations, assumptions, models, benchmarking, and quality evaluation results.

Each step described in the flow of work toward the development of the inventory database will be presented broadly in two parts. The first part presents guidance for each step of each task, while the second part presents discussion and commentary for each task, along with specific examples and recommended practices.

4.2 Guidance

4.2.1 Data-Collection Preparation

According to ISO 14044, the first step of data inventory analysis is preparing a plan for data collection; this plan outlines the specific procedures to gather required inventory data consistent with the goals of the study. The data types (primary or secondary) and quality requirements should be clearly defined in the scoping phase (see chapter 3) and in accordance with guidance provided in ISO 14044 (ISO 2006b). In addition, indicators of the representativeness of the data should be considered; data representativeness is measured by regional, temporal, and technological applicability of the collected data for the LCA application (discussed later). The procedure to determine data type and data-quality requirements is illustrated in figure 3-2 of chapter 3.

Data collection and inventory analysis plans generally include the following actions to ensure transparency and uniformity while minimizing misunderstanding:

- Development of a data management plan documenting data-collection processes, inventory reporting and updates, internal data-quality-control procedures, and responsibilities.
- Development of process flow diagrams that outline all unit processes, including their interrelationships.
- Preparation of data-collection forms and templates.
- Descriptions of each unit process in detail with respect to factors influencing inputs and outputs.
- Determination of lists of flows and relevant data for operating conditions associated with each unit process.
- Listing of the units of the flows.
- Identification of types of data for each unit process following the guidance provided in the scoping phase.
- Description of the data collection and calculation techniques needed for all data.
- Documentation clearly identifying any special cases, irregularities, or other items associated with the data provided.

Data-collection plans should also comprise the input and output flows for the included unit processes. The scope of input and output flows is governed by the impact characterization method chosen in the goal and scope phase. For example, emissions data can be limited to GHG emissions if the goal of the study is to calculate only global-warming potential (as opposed to a more complete list of impact categories). Major inventory categories for various processes that may be included in a pavement LCA are presented in table 4-1.

All the aforementioned measures emphasize the importance of planning and documenting the data-collection process, including consistency and uniformity. This will reduce potential errors and facilitate future referencing.

4.2.2 Initial Data Collection for Materials-Production Stage

Once the data types and data-quality requirements are determined and the data-collection plan is prepared, the next step is to perform the data collection for the material-production stage. The inventory list needs to consider all materials used in the system boundary. In addition to the inventory of pavement construction materials, plant processing energy requirements and emissions should also be collected. Plant processes may include asphalt plants (batch or drum mixing), concrete production (ready-mix and central-mix plants), and precast concrete production.

The following is a general introduction to data collection and recommendations; strategies for data collection of primary and secondary data are discussed separately.

Table 4-1. Inventory categories and parameters collected for each unit process included in the system boundary.

Flow Category	Description and Examples
Energy Input	Renewable and nonrenewable energy resources for primary and secondary data sources are typically reported separately. See the complete list of energy-related parameters in chapter 5 table 5-3. Examples: energy demand for the production and combustion of electricity, coal, gasoline, diesel, natural gas, and residual oil in various processes.
Raw Materials Input	Renewable and nonrenewable material resources are typically reported separately, as are primary and secondary or alternative material resources. Examples: minerals, metals, water and feedstock oil products.
Ancillary Inputs	Ancillary inputs are material inputs consumed by the unit process to produce the product, but that do not constitute part of the product. Examples: blasting and explosives used during quarrying operations.
Products Output	Products are any goods or services. Examples: pavement as the final product of pavement LCA, asphalt mixture produced in an asphalt plant, concrete mixture in a ready-mix concrete plant, and asphalt binder that is produced at the blending terminals or refineries.
Co-products Output	Co-products are any of two or more marketable materials, products or fuels from the same unit process, but which are not the object of the assessment. Example: slag as a co-product of steel production.
Waste Output	Waste is typically categorized as either hazardous or nonhazardous waste; radioactive waste is sometimes dealt with separately.
Emissions to Air	Emissions to air typically include GHG such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other air pollutants, such as particulate matter (PM2.5 and PM10), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOC) and heavy metals.
Emissions to Water	Emissions to water typically include nitrogen, phosphate (PO43-), chemical oxygen demand (COD) and heavy metals.
Emissions to Soil	Emissions to soil reflect emissions of oil, pesticides and heavy metals.
Other Output	Noise, radiation, land use and others.

Application

Following the definitions and guidelines introduced in chapter 3, if the goal does not require consideration of the full life cycle, initial data collection should be performed only for the life-cycle stages included in the system boundary. Initial data-collection guidelines presented in this section apply to the following scenarios:

- Cradle-to-gate studies which include materials extraction and processing (e.g., generation of EPD to characterize the environmental impact of a pavement material).

- Gate-to-gate studies which consider processing of a material in a plant (e.g., assessing variability in different plant production technologies to environmental product performance).

Data-Collection Methods

The data-collection phase is expected to be the most time-consuming, resource-intensive part of the LCA. The steps and option paths in collecting initial data are illustrated in figure 4-4 and are briefly summarized as follows:

- **Option 1 - Direct Measured Emissions (Primary Data):** Source-specific primary data with direct measured emissions are considered as option 1. This is likely the most expensive and the most reliable data that can be collected for a unit process if the measurement conditions are representative.
- **Option 2 - Process-Activity Data and Modeling with Emission Factors (Primary or Secondary Data):** This option can be used for collecting primary and secondary data. The actual data collected are process-activity data, such as energy consumed, products, hours of operation, productivity, etc. Primary (Option 2A) or secondary (Option 2B) data (see figure 4-4) can be collected as process-activity data. For example, for an asphalt plant, input data for Option 2A can be the energy sources and consumption for the specific plant producing the asphalt mixture used in the construction of pavement studied, while secondary process-activity data (Option 2B) can be average energy consumption for all counter-flow, drum-type asphalt plants in the U.S. In general, process-activity data collected in Option 2A will be more representative than those collected in Option 2B. An additional data modeling step is required to convert the process-activity data to desired output data (e.g., CO_2 emissions) using emission factors. The emission factors can be either from the literature (e.g., EPA 1995) or databases in commercial software (e.g., Ecoinvent [EarthShift 2013] or Gabi [Baitz et al. 2013]). Overall data quality of inventory results obtained from Option 2 is dependent on both the process-activity data and the degree to which the emission factors are representative. In general, the reliability and representativeness of the inventory results decreases from Option 1 to 2 and from Option 2A to Option 2B.
- **Option 3 - Financial Activity Data and Modeling with Emission Factors (Secondary Data):** This option also needs the data modeling step that converts the input data (e.g., the dollar value of purchased fuel) to the desired output data (e.g., CO_2 emissions). The emission factors can be from Economic Input-Output Life-Cycle Assessment (EIO-LCA) tool developed by Carnegie Mellon University (CMU 2002). These models are approximate and should only be used for missing pavement LCA data that cannot be collected by other methods. Discussions on how EIO-LCA may be used in pavement LCAs are provided by Hendrickson, Lave, and Matthews (2006) and Santero (2009).

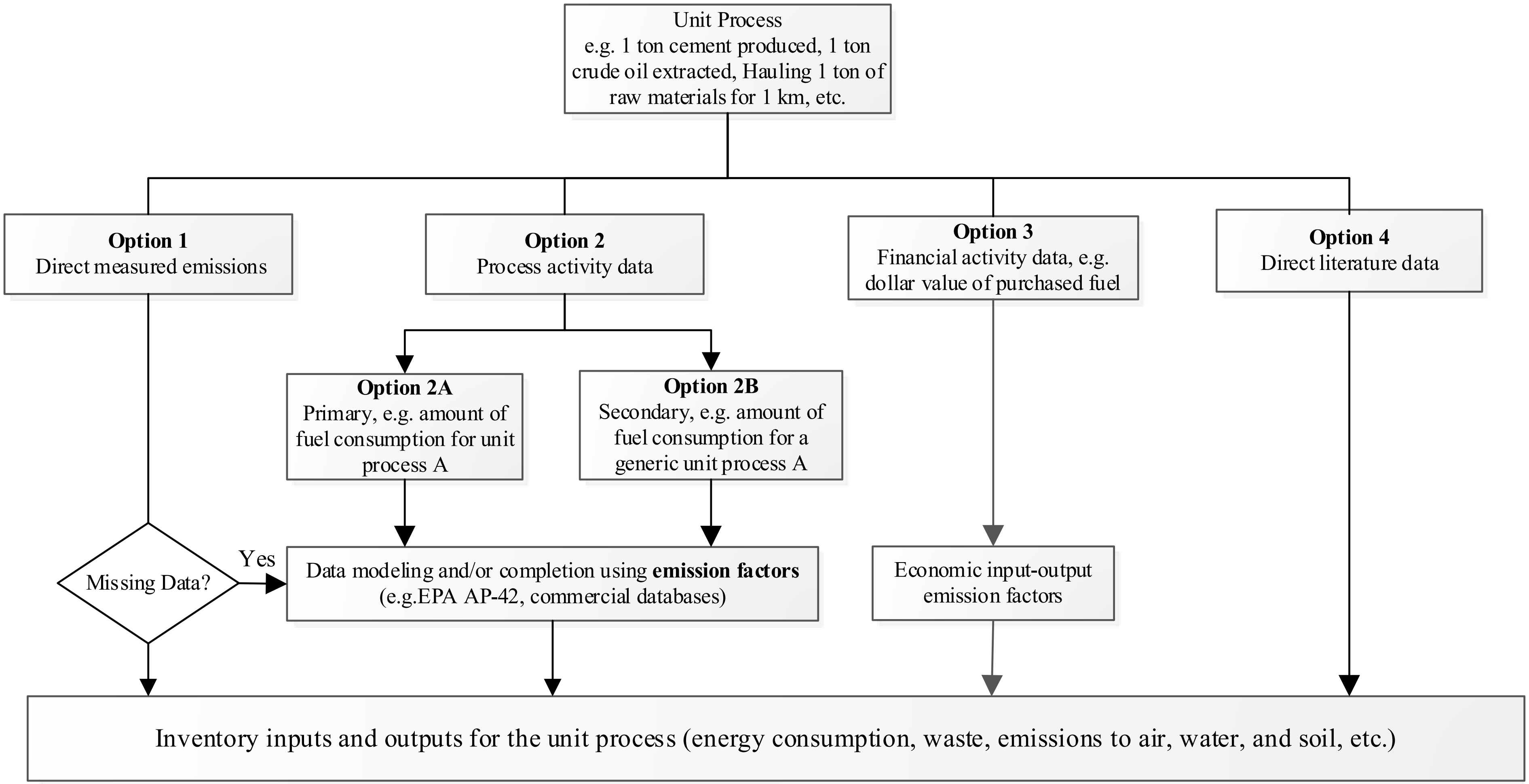


Figure 4-4. Data-collection and calculation options to achieve LCI database for each unit process included in an LCA (adapted from GHGP 2011).

- **Option 4 - Direct Literature Data (Secondary Data):** When process-activity data are not available to the initiator or the practitioner of the LCA, data from the literature and publicly available databases and sources may be used. This may range from primary data reported in the databases to proxy data when only similar (but not identical) material or process data are available. However, special attention is needed when proxy data are used, as data sources should be checked for their representativeness and transparently reported with the inventory results.

The path to reach the inventory inputs and outputs may vary depending on the unit processes and the type of data (primary or secondary) targeted for a specific unit process. Regardless of the selected path, the final inventory data should include the list of inputs and outputs originally defined by the goals of the study.

A summary of recommendations for the application of data-collection options for various pavement LCA phases is provided in table 4-2 for the processes categorized as upstream, downstream, and under control of the initiating party of the LCA. Upstream processes for material acquisition and production stage for pavement LCA typically refer to the processes associated with extraction of raw materials used in the production, whereas downstream processes for pavement LCA generally include the processes that may take place during the construction and service life of pavements (i.e., construction, use, and end-of-life stages). Secondary data may generally be used for upstream and downstream processes where collecting primary data may not be possible. Interpretation of the recommendations presented in table 4-2 can also differ depending on the goal of the LCA and its applications; for example, a paving contractor might use primary data for the construction process and secondary data from the raw material and material production. On the other hand, if a project- or network-level LCA objective is assessing road roughness and its impacts on the pavement life cycle, the use stage should be the process with primary data and other life-cycle stages may be considered with upstream and downstream processes. Potential LCA applications and corresponding separation for processes are presented later in this chapter.

Table 4-2. Application of data-collection options for the primary and secondary data.

Data Requirements	Upstream Processes	Downstream Processes	Processes Under Control of Initiating Party
Data Type	Secondary (or generic) data	Secondary (or generic) data	Primary (or specific) data
Data-Collection Option	Options 2, 3 or 4. Example: Electricity production directly from US-LCI (Option 4) or regionalized electricity production using eGRID and US-LCI (Option 2)	Option 4 Example: Gasoline combustion in passenger cars (use stage)	Option 1 (preferred) and Option 2 can be used when direct measurement data cannot be made available. Example: Cement plant data provided by specific manufacturer (Option 1) or cement plant process activity provided by specific manufacturer and modeling with emission factors (Option 2)

Regardless of the final option selected, a data-quality assessment should be conducted using the data-quality indicators and criteria introduced and defined in the goal and scope document. In addition to the representativeness of the collected data, the quality assessment should consider the models and emission factors.

The inventory database provided in any available and applicable EPDs may alleviate some data-collection burden. EPDs are generally developed in two categories: industry wide and producer specific. EPDs that are industry wide are regarded as secondary data and may be used as is when compliant with data-quality requirements. In the case of EPDs that are producer specific, the data provided may be considered as primary data if the specific producer or product is among the potential producers for the particular pavement LCA.

Primary Data-Collection Strategies

Primary data refers to data derived from specific processes in the LCA that, as a minimum, are owned or under the direct influence of the commissioning party, but can also include other processes and materials where relevant. Some examples are inputs and outputs from cement manufacturing plants, aggregate quarries, and asphalt plants. Collecting the data and ensuring that they conform to the data requirements should be completed in an iterative manner using the following general steps:

1. Collecting data at the production site (either direct emission measurements or activity data) using the questionnaires and templates (e.g., general production and operation details, annualized input and output flows per reference unit).
2. Converting all inputs and outputs to the appropriate reference unit (e.g., gallons of diesel per metric ton of cement production, short tons of CO_2 per metric ton of asphalt mixture production).
3. Determining the statistical distribution (e.g., normal or log normal) of the collected data.
4. Calculating the missing emissions data using a method consistent with data-quality requirements (when only activity data are collected or measured emissions are not sufficient to calculate required impact categories). This method can use emission factors in the public literature (EPA 1995) or commercial databases. The steps to perform data completion and modeling are described in the next section.
5. Preliminary screening of the collected and modeled data for reasonableness using literature sources or historical data.
6. Communicating with the owner or the supplier of the data to clarify potential ambiguities.
7. Finalizing the primary data collection for the product or unit process with documentation of collected and calculated data and other details outlined in the data management plan.

The use of industry questionnaires and templates is recommended as a means to collect the primary data. The data collection or questionnaires are generally arranged into several categories. The first category is general information regarding the collected data and source. Whether data are collected from industry questionnaires or open source databases, the following information should be included to help facilitate data acquisition, improve consistency, and reduce errors:

- Reference unit for the data collected (per kg of cement, short ton of binder, etc.).
- Geographical location of the source of data or facility.

- Applied technology and production details.
- Description of the production steps to indicate what data are included/excluded in order to be consistent with the system boundaries of the unit process.
- Allocation method if it is already performed on the collected data.
- Data necessary for allocation to different products (for example, volume and economic value of each product in a specific period).
- Period of data collection.
- Calculation method (e.g., yearly or monthly measurements, calculated from recorded consumption of fuels and electricity, or estimated). This information can be repeated for each single input or output if variations exist. Data-quality indicators and uncertainty of collected each input or output should be targeted with such information.
- Validation procedure for each input and output collected.
- Specific instructions on collecting data and completing data-collection sheets if industry questionnaires are used.

The second category is related to the inputs and outputs for each unit process. Inputs may include raw materials, ancillary materials, water consumption, fuels, and electricity, while outputs may include products, co-products, solid waste, emissions, and other environmental aspects. Since each unit process may exhibit significant variations, data-collection sheets can be modified for a specific process. In general, available information that can be collected from industry is the consumption of fuels and electricity, products and co-products, and solid waste. Some industries keep detailed inventory lists to meet EPA requirements, such as in the case of GHG reporting requirements (GPO 2009). Therefore, in the first round of data collection for primary data, the data may generally include only some of the inputs and outputs defined previously in table 4-1. The scope of primary data collection may be extended to direct emission measurements, depending on the data-quality requirements.

A third category is the transportation inherent in all inputs defined in the system boundary of the unit process. In this category, the upstream (supply chain) and internal transportation are generally targeted with the data-collection sheets. It is recommended that the transportation of all input materials and fuels be included, and with the following types of information:

- Distance transported from origin (or origin location should also be requested).
- Transportation mode (e.g., road, rail, or barge).
- Truck capacity (if road transport).
- Actual or estimated load of trucks (if road transport).
- Empty return (this can simply be a Yes/No question or a percentage).

In addition, transportation-related feedback is required for in-plant transportation. In-plant transportation usually involves the use of vehicles such as wheel loaders, hauling trucks, scrapers, dump trucks, and forklifts for operations like stockpiling. The information requested can be the type of equipment used for the in-plant operations, the total amount of fuel consumed (e.g., diesel oil, gasoline, or liquefied petroleum gas), and the total amount of material transported or processed.

Secondary Data-Collection Strategies

When primary data for a unit process are not available or are not required in the goal and scope, other data sources (open-source databases or commercial life-cycle databases) can be used to fill data gaps in the primary data and to model downstream and upstream data, including scenarios for the use and end-of-life stages. In this regard, there are many possible sources for secondary data. Examples are life-cycle databases, published product inventory reports, reports from government agencies, industry association reports, and other published literature.

The steps to collect secondary data follow an approach similar to that applied for the collection of primary data (steps 1 to 6). The secondary data can also use direct emissions measurements or activity data that are not specific to the processes studied in the LCA. The secondary data can sometimes be used as is, or may be modified according to the scope of LCA and data-quality requirements.

In general, the following steps can be used to collect secondary inventory data:

1. Select the secondary data source consistent with the data-quality requirements (e.g., commercial life-cycle databases, published product inventory reports, reports from government agencies, published academic papers or reports, and industry association reports).
2. Convert all of the inputs and outputs that are not already converted to the selected unit in the data source (e.g., gallons of diesel per metric ton of cement production, short tons of CO_2 per metric ton of asphalt mixture production).
3. If the secondary data source includes all of the required inputs and outputs and is consistent with the system boundary of the studied process and data-quality requirements, proceed to Step 5.
4. If the inputs and outputs in the data source are not sufficient or not consistent with the system boundary of the studied process and data-quality requirements, modify the secondary data by completing the missing data and improving the data quality. This process requires the availability of critical input data related to raw material and energy consumption (in other words, all or some of the activity data). Following similar protocols outlined for primary data collection, secondary data can be modified using emission factors as explained in the next section. If process-activity data are not available, best matching proxy data for the product of unit-process-secondary data can be used.
5. Perform preliminary screening of the collected secondary data for reasonableness using other literature sources.
6. Finalize the secondary data collection for the product or unit process with documentation of the collected and calculated data and metadata.

It is important to maintain detailed documentation for the secondary data by providing some level of metadata (i.e., data about data). Metadata include information on data collection, system boundary, and year of data collection. Minimum requirements for metadata include the name of the unit process, category, description (reflecting system boundary), location, LCI method, data-quality indicators, data sources, restrictions, data owner, data created, and last update.

4.2.3 Initial Data Collection for Other Life-Cycle Stages

Applications

If the intended goal of the study is to perform an LCA that requires consideration of the full life cycle (such as comparing the environmental impact of two pavement construction or rehabilitation alternatives), inventory data will be needed for other life-cycle stages of the pavement alternatives. The following scenarios require data collection at one or more life-cycle stages in addition to the material extraction and production stage:

- Cradle-to-grave LCAs with complete life-cycle stages included in the system boundary.
- Cradle-to-gate LCAs with options (which includes the production stage and selected further life-cycle stages).
- Cradle-to-laid (also referred to as "cradle-to-end of construction") LCAs with the construction stage added to the system boundary.
- Specific parts of the life cycle (e.g., waste management, components of a product, use stage).

In general, the principles and guidance already provided apply to other life-cycle stages as well. However, data-collection strategies, data features, and data attributes can exhibit some differences with respect to each life-cycle stage.

The types of data collected for each life-cycle stage are discussed in this section. After the collection of data from different sources, inventory data are processed according to the steps described for primary and secondary data. This is the preliminary processing of raw data collected from various sources to estimate the complete input-output flows (if they are missing), verification of the data for consistency with the system boundary assumptions, and reasonableness.

Data Collection for the Construction Stage

Data for specific project tasks and construction unit processes in the construction stage should be assembled. Due to the difficulty of collecting primary data for construction processes in the form of direct measurement of emissions from the equipment during a construction process, generally data-collection options 2A and 2B are recommended. Key steps in performing an inventory analysis for the construction stage are the following:

1. Obtain data for the project and construction processes. The data may include productivity rates, fuel consumption, load factors, horsepower, operating time, age, and other characteristics for individual equipment and for overall project tasks, as appropriate.
2. Calculate fuel needed for each task. A list of equipment should be designated for each task, and the fuel consumption is calculated using the data obtained in the previous step. Fuel needed (also referred to as the "fuel factor") is generally defined in terms of operating duration, load factor, horsepower, fuel efficiency, and productivity rate.
3. Create unit processes using emission factors available in commercial databases such Ecoinvent or Gabi and EPA-based databases and tools, such as EPAs NONROAD (EPA 2008b) and California Air Research Board's (CARB) OFFROAD for each equipment (CARB 2007). The unit process for each equipment can be defined in terms of input-output flows per hour use of specific equipment.

4. Aggregate unit processes to develop input-output flows for a construction task. Each construction job in the project can consist of one or more tasks. Each of these tasks can be associated with a productivity rate (units dimension per hour). Thus, the equipment specific input-output flows per hour should be summed, giving the total input-output flows per hour for each task.

The level of detail required for the construction stage depends on the goals of the LCA. In project-level LCAs, detailed construction activities should be documented to include (but not be limited to) the following activities:

- Equipment usage at the site for construction activities (e.g., milling, pavement removal, excavation, stabilization, placement of fill, placement of drainage, embankment, base trim, asphalt mixture placement, tack coat application, placement of concrete, placement of barrier walls, shaping of grades/ditches).
- Unit of service delivered (e.g., square yard [SY], cubic yard [CY]).
- Equipment type and amount.
- Fuel type and consumption used by equipment.
- Productivity hours per day (calculated based on working hours).
- Load factor/power factor of each equipment.
- Idle time of equipment.
- Fuel efficiency of construction equipment used in all construction activities.
- Transportation of materials and equipment to the site (mobilization impact).
- Material resource location matrix.
- Water transport and use.
- Energy used for lighting (for night construction).
- Work-zone-related traffic delays.
- Construction-related closure strategies for construction/reconstruction/maintenance activities.
- Building of any temporary infrastructure.

Data Collection for the Maintenance and Rehabilitation (M&R) Stage

The number and timing of maintenance and rehabilitation activities in the life cycle is needed for cradle-to-grave studies (if they change the unit processes or emissions per unit of production), and are often included in cradle-to-gate and cradle-to-laid studies that consider the frequency of M&R treatments over a given analysis period. There are two approaches for developing performance estimates:

- Use existing performance prediction models or develop them using historic pavement performance data or mechanistic-empirical analysis. Performance can be defined in terms of overall condition index, specific distresses, roughness, and texture.

- Use pavement preservation schedules and maintenance and rehabilitation schedules, or planning reports. Planning reports can include scheduled activities during the service life of the pavement.

Pavement Performance Data and Prediction Models

Pavement performance data usually include structural and surface characteristics, such as roughness and texture. In addition, some type of condition index indicating overall condition of pavement (e.g., pavement condition index [PCI] or condition rating system [CRS]) can be collected specific to the pavement type in the scope of LCA performed. A detailed review of pavement condition performance models and data-collection guidelines is discussed by Wolters and Zimmerman (2010) and by Pierce, McGovern, and Zimmerman (2013). Specific guidance on the type of performance inventory data should be collected; recommended approaches are provided in AASHTO's pavement management guide (AASHTO 2012).

The performance data should include progression models for predicting pavement future condition utilizing historical traffic and environmental regional data. Even though agencies have been collecting field performance data, prediction models may not be available. In the case that models are unavailable, historical performance information will need to be collected to build such models for the pavement type studied. When the field performance data do not exist or are not considered sufficient, existing models can be extended using the available information in the literature to ensure reasonableness. For example, pavement management programs for most state and local highway agencies use one type of overall pavement condition index and IRI. Macrotexture is less frequently collected, but may become increasingly available with the increased use of automated pavement data-collection vehicles.

An alternative to the use of PMS data to develop performance models is the use of calibrated mechanistic-empirical (ME) models. ME models must be used when the pavement structure, material or treatment being considered has not been built in the past, or when other variables such as traffic loadings (change of vehicle, tire or other technology) and climate are not well represented in historical data and hence have limited (if any) field performance data available.

Depending on the agency's practices, if such a planned schedule for the sequence of maintenance and rehabilitation activities does not exist, one should be established using the prediction models and trigger values. In addition to that application, performance models can be used to ensure equivalency of the two pavement types if a comparative LCA is conducted. Moreover, functional performance models (roughness and texture) provide input for the use-stage fuel-consumption analysis. Finally, when a network level LCA is conducted, pavement performance models provide an indication of the overall network health in term of average remaining service life or average roughness levels.

Some of the specific attributes of the pavement performance models recommended for pavement LCAs are listed below and summarized in table 4-3:

- Prediction models should provide progression of the performance data (e.g., IRI, Mean Profile Depth [MPD], or overall condition index) throughout the service life of the pavement until the next major treatment following the original construction. Prediction models can be developed for a newly constructed or rehabilitated pavement.
- When the analysis period encompasses maintenance and rehabilitation activities, the effect of major treatment activities should be included in the models. The effect can be in

the form of a change in the pavement condition right after the treatment and followed by a change in the pavement deterioration rate. If such prediction models are not available, inventory data should be requested to help develop required models. The data required are pavement condition before and after specific treatments representative of the original pavement type. Examples of such progression models are provided in the commentary section.

- Prediction models should reflect site-specific conditions for project-level LCA applications. These conditions include realistic traffic estimates and impact on the performance data and environmental conditions. Even though the designs are the same, pavement performance may significantly vary in a network due to applied traffic, truck volume, environmental conditions, subgrade type, quality of materials available regionally, type and frequency of maintenance and rehabilitation activities, and construction quality. Therefore, network-level prediction models are not recommended for project-level LCA applications. Site-specific, pavement-performance prediction models should be developed. Agencies commonly develop network-level performance prediction models for making high-level decisions.
- Family-type performance-prediction models (indicating average network performance of one pavement type) can be used for network-level LCA applications. These are generally models developed for different types of structural designs existing in the network, with some regionalization to reflect traffic, materials, or climatic conditions.
- Structural evaluation data providing structural stiffness and material strength properties can be incorporated in the use-stage calculations in relating structural response to rolling resistance. Backcalculated modulus data or deflection basins obtained from the pavement deflection testing (using falling weight deflectometers [FWD] or rolling weight deflectometers [RWD]) can be utilized in evaluating rolling resistance due to structural response. [It is noted that backcalculation procedures for asphalt-surfaced pavements for determining rolling resistance must provide viscoelastic properties, which requires time histories of deflection (rather than the standard practice of only collecting peak deflections) and the use viscoelastic backcalculation procedures (in lieu of standard elastic backcalculation methodologies)].

Representative site-specific field-measurement inventory should be used in developing an inventory for project-level assessment, whereas network-level averages for the same family of pavement structure can be used for network-level applications. Other field data are often required to determine thicknesses and material properties needed for the determination of structural response.

Table 4-3. Performance measures required and their uses in various pavement LCA applications.

Performance Parameter	Use in LCA
Overall condition index (e.g., PCI, CRS) or Other Performance Measures (e.g., cracking, faulting, rutting)	• Predict service life of a pavement to establish equivalency for comparative LCAs. • Determine an analysis period covering a specific segment of predicted service life. • Design of maintenance and rehabilitation schedule when overall condition index is used as trigger.
Roughness (IRI)	• Provide input to the use stage to calculate pavement-related rolling resistance. • Design of maintenance and rehabilitation schedule when IRI is used as trigger.
Macrotexture (MPD)	• Provide input to the use stage to calculate pavement-related rolling resistance. • Design of maintenance and rehabilitation schedule when friction is used as trigger.
Structural response-related parameter (e.g., surface deflection basin)	• Provide input to the use stage to calculate pavement-related rolling resistance. Inputs can include parameters to perform structural analysis and convert relevant pavement responses to excess fuel consumption.

Pavement Maintenance and Rehabilitation Schedule

The data collection for future activities should include documentation of all of minor and major scheduled activities anticipated for the maintenance and rehabilitation stage of the pavement LCA. The data should include the type of activity (e.g., sealing, routing, patching, overlay, slab replacement, reconstruction, etc.) and the frequency or timing of each activity, as summarized in table 4-4. If a scheduled set of activities does not exist for the pavement studied, then an anticipated schedule of activities should be developed using the performance prediction models and historical activities for similar pavements representative of the project site conditions. The progression models discussed in the previous section can be used to develop a maintenance schedule. Those highway agencies that perform life-cycle cost analysis comparisons for alternative new pavement and rehabilitation projects will often have M&R schedules. Examples of planned activity schedules are provided in the discussion section.

Table 4-4. Maintenance and rehabilitation parameters collected for each activity.

Maintenance Parameter	Unit (Expressed per Functional Unit)
Maintenance Process	Description or source when description can be found
Maintenance Cycle	Number per analysis period
Unit	Length, area, or volume expressed as a percentage of the affected pavement element
Processes Included	Transportation, materials consumed, construction activities

Once the maintenance and rehabilitation schedule is developed, the inventory database used for the materials and construction stages is generally used for this stage. Some pavement LCAs use actual applied activities based on work and change orders for historic activities.

The steps followed to develop inventory input and output flows for the construction stage should be repeated for each maintenance and rehabilitation activity.

Data Collection for the Use Stage

The use stage of a pavement life cycle includes everything that occurs while the pavement is in operation, and is affected by the pavement's structural and material properties as well as its surface characteristics. Possible considerations of the use stage relevant to a pavement LCA include rolling resistance (e.g., tire-pavement interaction, vehicle-pavement interaction affecting suspension system, pavement deformation), albedo, carbonation, lighting demand, and leachate, the inclusion of which will depend on the goal and scope of the study.

Data collection in the use stage differs from the other stages in that it requires additional modeling steps to define the interaction between vehicles and surface and structural response of pavements with the environment as well as the interaction of the pavement itself with the environment and other human systems (such as heating, cooling and lighting). Data collection for the use-stage components consists of three major steps:

- Pavement characteristics: Development of physical, mechanical, and thermal properties of pavement surface characteristics interacting with the environment and vehicles.
- Use-stage impact: Identification (if they exist) or development of models relating pavement surface and structural characteristics to intermediary pavement use-stage impacts (e.g., the effects of roughness and macrotexture on pavement-related rolling resistance of vehicles or the effects of albedo changes on urban heat island and energy use in buildings).
- Emission factors: Identification of models to convert intermediate use-stage impacts to calculate life-cycle inventory input-output flows (energy consumption, emissions, etc.) consistent with the other stages (e.g., energy demand or GHGs resulting from pavement-related rolling resistance or urban heat island).

Some of the use-stage components that define the interaction between environment and pavements are shown in table 4-5. Data-collection strategies and recommendations for each component are discussed in the following section.

Table 4-5. Common use-stage components and relevant parameters used in pavement LCAs.

Use-Stage Component	Relevant Input Parameters	Energy/Emission Model	Inventory Parameter
Vehicle Fuel Consumption	• Traffic mix, volume and growth • Traffic speed distribution and its sensitivity to roughness and texture • Fuel economy for each vehicle type • Pavement type • Roadway functional classification and geometric features (needed for vehicle emission simulations) • Progression models for roughness and texture • Material and structural energy dissipation characteristics	Pavement-related rolling resistance models: • Roughness energy/emissions • Texture energy/emissions • Structure energy/emissions	Change in vehicle fuel consumption and emissions due to change in pavement surface properties and structural response
Heat Island	• Pavement surface material albedo progression • Solar radiation • Permeability • Conductivity • Heat capacity • Emissivity • Regional power demand for AC use • Temperature history • Climate data and effect of albedo on temperatures	Urban canopy model to determine temperature changes due to pavement thermal properties and energy use/temperature relationship Building energy use as function of temperature	Change in emissions at site and at location of energy generation due to change in energy use and its timing (peak, off-peak, etc.)
Radiative Forcing	• Pavement surface material albedo progression • Surface area	Radiative forcing change per unit surface albedo change	CO_2 offset or gains due to pavement surface albedo changes
Lighting	• Illumination demand • Surface area of pavement • Reflectivity of pavement • Total usage	Technology efficacy (lumen/kWh)	Electricity consumption and emissions due to roadway's illumination demand
Carbonation	• Pavement type and porosity • Temperature and humidity • Cement content and composition	Fick's diffusion model carbonation rate	Sequestered CO_2

Vehicle Fuel Consumption

Pavement surface characteristics can influence vehicle fuel consumption through three major mechanisms of interaction between vehicles and pavements. The additional rolling resistance caused by pavements is called pavement-related rolling resistance (Van Dam et al. 2015). The three mechanisms are related to roughness, macrotexture, and structural response of pavements affecting rolling resistance of vehicles and, hence, fuel consumption.

Step-by-step procedures to gather relevant data and include pavement-related rolling resistance in the LCA are as follows:

1. Gather traffic data for the pavement section including traffic volume and speed distributions for individual vehicle types during the day; fuel efficiency for each class of vehicle and their sensitivity to pavement characteristics; and future predictions for these traffic variables (constant growth or other scenarios).
2. Obtain pavement-related data including pavement type, age, material types and layer thicknesses for use in macrotexture and roughness-progression models and for use in calculating pavement-structural response.
3. Obtain typical pavement temperature data for pavement types and layer thicknesses in the study to calculate pavement-structural response; include distributions across the day and across all seasons. This allows assessing interaction with traffic flow and speed data.
4. Procure pavement geometry characteristics, prevailing geographical conditions, and roadway functional classification. These characteristics are needed in performing specific vehicle simulations tools such as EPA's MOVES (Motor Vehicle Emission Simulator).
5. Gather performance prediction models describing the progression of surface characteristics (roughness and macrotexture) consistent with the performance model guidelines introduced in the maintenance and rehabilitation stage. These models should be capable of predicting performance (e.g., change in IRI and MPD) in the analysis period of the pavement and should also be representative of the site-specific conditions for a project-level LCA application. When performance models do not exist, historical data should be requested from the agency to develop progression models for the same section or similar pavement sections. When applicable, differentiate the models predicting driving- and passing-lane surface characteristics.
6. Identify pavement-structural response characteristics that may potentially contribute to structural responsiveness-related rolling resistance. There are different versions of models available in the literature relating pavement-structural response to vehicle fuel consumption (Akbarian et al. 2012; Pouget et al. 2012; Chupin, Pian, and Chabot 2013). Depending on the selection of model, the input requirements may vary. For example, the viscoelastic properties of asphalt materials (relaxation characteristics or stiffness and phase angle) and the damping properties of soils under concrete pavements are considered in current models. Inputs required for rigid and flexible pavements may vary.
7. Define the roughness- and texture-related rolling resistance energy/emissions model for each vehicle class included in the goal and scope. These models are generally defined per each vehicle distance travelled on a certain pavement having defined surface and stiffness characteristics at a specific vehicle speed (e.g., gasoline consumed per mile passenger car travelled at a speed of 50 mi/hr on a road with IRI of 60 inches/mi). The rolling-resistance, energy-emission models are generally defined using an incremental relationship indicating

the change in fuel consumption or emissions for a change in pavement properties. The required complexity level of vehicle and pavement interaction is defined in the goal and scope phase. Vehicle operation conditions (acceleration, deceleration, idling, or steady-state speed, etc.) and the interaction between the vehicle and pavement properties and fuel consumption can be considered in developing rolling resistance models. EPA's MOVES software provides a comprehensive platform to calculate the relationship between vehicle operating conditions and energy/emissions (EPA 2014a). When the vehicle specific power and rolling resistance models in the software are calibrated using the HDM-4 models, the roughness and texture effect can be incorporated. The outcome of MOVES software includes energy consumption, GHG, and other emissions that can be used in calculating the impact categories for each vehicle operation condition and pavement properties. Alternatively, calibrated HDM-4 (Chatti and Zaabar 2012) models describing IRI and fuel consumption relationship can be used if the assumption of steady-state speed of vehicle operating conditions is consistent with the goal and scope.

8. Aggregate data for the pavement section and given traffic information for the analysis period chosen. The rolling resistance models obtained in Step 7 are combined with the pavement and traffic data to calculate total energy and emissions for the functional unit (i.e., 1 lane-mile for an analysis period of 40 years). The VMT or VKT (vehicle miles travelled or vehicles kilometer traveled) obtained in Step 1 should be used with the initial roadway functional characteristics (Step 3) and performance models for surface characteristics (Step 4) to calculate total use stage roughness- and texture-related inventory outputs using the emission models described in Step 6. The outcome is then the additional energy consumed or additional emissions released per vehicle miles traveled each year for a corresponding change in roughness and texture. It is important to note that the total energy or emissions do not need to be reported, but only the additional amount of energy or emissions due to roughness and texture changes. All of these parameters and models include future predictions, so some degree of uncertainty is inherent.

9. Define pavement-structure response related to rolling-resistance, energy-emissions model and perform structural-response simulations. The models should relate the pavement's structural response to excess fuel consumption of different types of vehicles (Akbarian et al. 2012; Pouget et al. 2012; Chupin, Piau, and Chabot 2013). Major determinants of the model are vehicle loading and speed, as well as environmental conditions affecting pavement response (daily and seasonal temperature fluctuations, moisture of granular and soils materials, etc.). Pavement-structural simulations are required considering the major determinants. The complexity of the simulations (layered elastic, layered viscoelastic, or three-dimensional finite element) is driven by the model chosen to relate pavement-structural response to fuel consumption. Simulation resolution may vary from hourly distribution to typical values across the day for each month to capture interactions of vehicle flows and speeds, temperatures, and other environmental conditions. The level of resolution in the simulations should be selected by considering time and computational constraints as well as the goal and scope of the study. Simulations are conducted with the major determinants considered as inputs with their future predictions. Then, the obtained pavement responses are related to vehicles' excess fuel consumption with the chosen rolling resistance energy/emissions model. Excess fuel consumption can be converted to emission using appropriate emissions factors defined for moving vehicles (EPA 2008a or Ecoinvent 2016). The outcome can be represented by energy and emissions per yearly vehicle miles traveled.

10. Combine the three components of pavement-related rolling resistance (i.e., structure, roughness, and texture) to report the inventory inputs and outputs on a yearly basis with the numbers accumulated from previous years.

Radiative Forcing

The term "radiative forcing" was employed in the IPCC assessments (IPCC 2001) to denote externally imposed perturbations in the radiative energy budget of the Earth's climate system. These perturbations can be caused by atmospheric emissions (e.g., CO_2, air pollutants) as well as by changes in surface reflection properties, resulting in an imbalance in the radiation budget (differences between absorbed and reflected radiant energy) and leading to changes in the climate system. The measure of radiative forcing (RF) is watts per meter square (W/m^2). Positive radiative forcing warms the system whereas negative forcing is cooling. The factors contributing to radiative forcing include solar irradiance, atmospheric aerosols, GHGs, cloud microphysics, and surface albedo due to changes in land cover (Cubasch et al. 2013; Van Dam et al. 2015). The effect of pavement on the radiative forcing can be represented by changes in albedo and land cover resulting in direct changes in radiative forcing, as opposed to indirect changes such as in caused by human activities due to the thermal performance of pavements (e.g., increasing energy use in buildings).

It is important to note that radiative forcing is accepted as a simple modeling concept to account for the relative impact due to different natural and anthropogenic radiative causes upon the surface-troposphere system. This modeling concept is framed with some restrictions and assumptions in the context of climate change (IPCC 2001). Among the factors affecting radiative forcing, there is lower confidence in the values relating surface albedo changes (due to a host of factors affecting land use changes, including deforestation, loss of ice caps and increases in open ocean area, agricultural practices, snow cover, and urban structures, among others) to climate change. The low confidence reported for the effect of land use changes in the IPPC assessments (2001, 2007, and 2013) is due to the small number of investigations and uncertainty in historical land cover changes in preindustrial and present times. The mechanisms behind radiative forcing are complex and vary for different parts of the earth due to changes in albedo from natural and anthropogenic causes and because of differences in solar radiation and cloud cover, resulting in spatial variability.

The relationship between surface albedo changes and radiative forcing is still a topic of major research. A general and simplified framework is presented here to quantify the effect of pavement albedo changes through radiative forcing.

The major inventory parameter to calculate is CO_2 offset or gains with changes in surface albedo. The relationship between surface albedo changes and radiative forcing is complex and often interacts with other contributing mechanisms to radiative forcing, such as cloud cover. A very rough relationship was established between surface albedo changes and radiative forcing by Akbari, Menon, and Rosenfeld (2009). An average reduction of 1.27 W/m^2 was calculated for an albedo increase of 0.01 for the average cloud cover over the earth and global mean forcing values (Akbari, Menon, and Rosenfeld 2009). This should be viewed as an estimate and an oversimplified calculation of a very complex phenomena, but it gives an approximate range of offsets or gains on the global-warming potential when various cool pavement mitigation strategies are considered. More details on the limitations and criticisms of these assumptions are provided in the commentary section.

With the resulting changes in the RF based on a change of surface albedo under average conditions, total changes in the atmospheric or emitted CO_2 can be adjusted. The range for emitted carbon dioxide equivalent (CO_2e) offset for 0.01 increase in albedo of urban surface is 2.55 to 4.90 kg CO_2 /m^2 (Akbari, Menon, and Rosenfeld 2009; Santero 2009). As an example, for a change of 0.15 albedo increase, the range of CO_2 offset would be 38 to 74 kg CO_2 /m^2.

Required inventory parameters in order to calculate RF-related CO_2 offsets or gains are surface type, range of albedo over the pavement life (until next treatment, if it is an original construction), and range of pavement or treatment life. The procedure to calculate RF-related CO_2 adjustment is given as follows:

1. Determine the range of surface albedo for the original pavement surface and over its service life. Field measurements can be used to take measurements in the same region with similar pavement type and surface materials. If field measurements cannot be taken and representative historical data do not exist, the expected range of values existing in the literature can be used as references. It may be that surface albedo measurements in the future will be routinely collected and become a part of pavement management systems, similar to texture and roughness measurements. That would allow for the range of albedo for different pavement surfaces to be more accurately determined from regionally representative historical databases.
2. Determine the range of surface albedo for every treatment planned in the analysis period of the pavement and their expected rates of change over the analysis period. Measurements from originally constructed representative pavement surfaces can be used for future treatments. When a historical database does not exist and field measurements are not an option, changes in albedo from an initial value for future treatments can be determined from literature sources or historical databases.
3. Determine the surface albedo of pavement to be replaced by the new construction or treatment.
4. Calculate the total CO_2 offset or gains by finding the difference between the mean value of albedo change after the construction until the next treatment and the old surface albedo replaced by the new construction. This calculation should be repeated every time the surface albedo changes due to rehabilitation activities. An equation for the CO_2 calculations is given below:

$$m_{CO2} = \sum_{n=1}^{N} 100 * \left(\alpha_{new}^{n} - \alpha_{ref}\right) * (f_{RF}) * A$$

where:

m_{CO2} *is the* total CO_2 offset or gain in kg over the analysis period.

a_{new}^{n} is the mean albedo value of the original pavement construction and subsequent treatments as an average value of initial albedo right after construction and final albedo before the next treatment.

a_{ref} is the reference albedo value, which can be taken as the albedo of the old pavement surface replaced by new construction or network average albedo. In comparative LCAs, the smallest albedo of compared surfaces can also be taken as the reference value.

f_{RF} is the CO_2 offset for an increase of 0.01 in albedo, in kg CO_2 /m^2. The range given in the literature for f_{RF} is between 2.55 and 4.90 kg CO_2 /m^2, corresponding to a reduction of 1.27 W/m^2 in radiative forcing for average cloud cover conditions (Akbari, Menon, and Rosenfeld 2009; Santero 2009).

A is the total surface area of new pavement construction in m^2.

N is the total number of treatment activities replacing surface layers during the analysis period.

Urban Heat Island

The urban heat island (UHI) effect is defined as the difference in temperature between urban areas and the surrounding rural areas caused by a variety of factors including a high concentration of dark and impermeable surfaces in heavily urbanized locations (Van Dam et al. 2015). UHI can affect communities by increasing summertime peak energy demand for air conditioning, influencing electrical grid reliability, affecting air conditioning costs, air pollution and GHG emissions, increasing heat-related illness and death, and affecting water quality (Van Dam et al. 2015). Among these impacts, the indirect effects of UHIs through increasing the energy use in buildings as a result of temperature rises in urban areas were quantified and may potentially be applicable to LCA applications (CARB 2013; Taha 2008, Pomerantz et al. 1999, CIRAIG 2010). Winter time increases in heating use due to reduced UHI must be inventoried at the same time as the summer time savings in energy use due to reduced UHI resulting in lower air conditioning use. The energy sources for air conditioning and heating must also be collected.

The relationships between the formation of UHIs and land surface type (e.g., pavements, parking lots, roofs, buildings, vegetation, tree cover, etc.) is complicated in urban environments due to the surface heterogeneity and the complex physics of urban canopies. There are number of ongoing studies investigating UHI effects that are expected to result in more sophisticated models that will provide more definitive results.

A general framework to incorporate the UHI effect requires the following data-collection steps:

1. Collect energy usage data from regional power companies to define a relationship between winter-time and summer-time energy demands due to heating, air conditioning, and temperature fluctuations. The power demand for AC usage (P_{AC}) can be extracted from the total electricity usage for all purposes. The outcome will be the change in power demand per unit temperature increase ($\Delta P_{AC} / \Delta T$ *or* dP_{AC} / dT if the relationship cannot be linearized).
2. Determine the change in temperature that a change in pavement albedo might cause (ΔT_{albedo}). Other pavement properties affecting thermal performance can also be considered, such as emissivity, heat capacity and thermal conductivity. The effect of these thermal properties on UHI is more complex and relatively less known. In order to obtain the change in temperature with albedo and other thermal properties of pavements, simulations may be required and can include urban canopy models (UCMs) that accommodate the effects of complex urban morphology and the mechanisms of thermal energy balance between different components of the urban fabric.
3. Calculate change in annual energy demand (in kWh/year or other sources of energy used in heating and cooling) due to changes in temperature resulting from pavement properties. The change in annual energy demand is proportional to power demand per unit temperature

changes ($\Delta P_{AC} / \Delta T$), change in temperature due to pavement albedo (ΔT_{albedo}), and number of hours used for cooling and heating. A current study defines cooling hours as CH18C, which is defined as the annual hours during which temperature is greater than 18 °C (Pomerantz, Rosado, and Levinson 2015).

4. Determine the required inventory outputs for the change in the electricity production using the electricity production inventory database. The same electricity inventory database used in the other stages can utilized. Changes in the consumption of other sources of energy used in heating and cooling of buildings should also be considered.

Data Collection for the End-of-Life Stage

Recycling, reusing, and landfilling are the three end-of-life scenarios that can be considered for pavements. On-site equipment use and transportation are the common activities for both options. The emission factors developed for construction activities and transportation are used to estimate burdens associated with both of these end-of-life processes with an appropriate allocation method selected in the scoping phase.

The cutoff method is commonly used as an initial estimator to allocate inputs and outputs for the end-of-life stage. According to this method, upstream producers do not receive any credits for producing recyclable materials. Downstream users (new pavement construction) are responsible for removal activities (e.g., demolishing, landfilling or transportation to a central facility) and receive the benefit of using recycled materials since it replaces the use of potentially more energy-intensive virgin materials. A more detailed discussion about allocating environmental burden to recycled or reused products is presented later in this chapter.

When landfilling is considered, the impacts include the burdens of transporting waste to the landfill site, as well as the leaching of waste once it is deposited. One EPA study on construction and demolition landfill leachate and water quality around several landfill sites found seven constituents of the 93 parameters emerged as being potentially problematic; however, none of the seven constituents showed any water quality impacts (EPA 1995). The study covered 21 landfills representing 1 percent of the total landfills in the U.S. at that time.

Construction and demolition debris resulting from pavement removal and reconstruction is typically considered as inert and nonhazardous waste unless reported otherwise. Historical construction records should be checked for verification. Then, the impacts from waste transport are likely to be the dominant effect of the landfilling process. Emissions from landfill and combustion are modeled using LCI sources like the WAste Reduction Model (or WARM) (EPA 2014b), and national estimates on average methane emissions, methane capture, methane flaring and heat, and electricity generation. Generic landfill models in commercial databases, such as Ecoinvent, can be used to benchmark and supplement data from these national sources (Ecoinvent 2016). The information shown in table 4-6 may be provided for all pavement products to support various end-of-life scenarios.

Table 4-6. End-of-life scenarios and processes considered.

Scenarios	Unit (expressed per functional unit)	Processes Included
Landfill	kg, collected separately	Demolition and transportation to landfilling facility and landfill
Recycled on-site	kg, recycled back to the same project	On-site handling processes, typically stockpiling, for the next use, which includes the recycling processes (milling, crushing, screening)
Recycled off-site	kg, recycled off-site	Demolition, transportation to and stockpiling at the central recycling facility
Reuse	kg, reused	Disassembly, transportation to and storage at the central collection facility (e.g., guardrail), in-place pavement processing (e.g., rubblizing)

4.2.4 Data Completion and Modeling

Initial data collection generally targets process-activity data in the case of primary data and secondary data for the upstream and downstream processes. However, occasionally primary data collected from the plants can also include direct emission measurements. When direct measurements are incomplete or missing, further processing of collected primary data is required to calculate the inventory outputs using the emission factors. A practical rule of thumb is to include those emissions that are part of formal reporting or permitting requirements, since those are based on generally accepted measurement protocols, reporting, and verification, and to add emissions from modeling or other sources to the list. Similarly, if there are missing data in the processes using secondary data, data need to be completed to satisfy necessary input-output flows to perform impact characterization. Data completion or modeling using emission factors are used in the following situations:

1. Primary data collected are direct measurements from a specific process with an incomplete list of emissions required for impact characterization.
2. Primary data collected only includes process-activity data.
3. Secondary data collected from identified sources only includes process-activity data.
4. Secondary data collected from identified sources includes process-activity data with an incomplete list of emissions required for impact characterization or incompatible data-quality requirements and system boundaries.

The steps required in the calculation of missing output flows are described below.

1. Identify processes from the data initially collected in steps 3 and 4 (indicated in figure 4-3 with missing output flows (e.g., in the case of only process-activity data collected) or an incomplete list of output flows (e.g., direct measurements with incomplete list of emissions or incomplete data from secondary source).
2. Use the emission factors identified in the scoping phase to model the processes and calculate a complete and desired list of emissions.
3. Match the emissions with the existing collected data (if any). If there are any overlaps, keep those from direct measurements.
4. Complete the input/output flows with the data collected in steps 2 and 3 (indicated in figure 4-3) and calculated in this task.

The sources of emission factors can be life-cycle databases (e.g., Ecoinvent [2016], US-LCI [NREL 2015], GaBi [Baitz et al. 2013], and ELCD [JRC 2006]), published product inventory reports, government agency sources (e.g., EPA AP-42 [EPA 1995] and EPA MOVES [EPA 2014a]), industry association reports (Marceau, Nisbet, and VanGeem 2006; Marceau, Nisbet, and VanGeem 2007; and World Steel 2011), and peer-reviewed literature. It is important to note that not all of these sources may be appropriate for primary data. Therefore, some of these emission factors will be referenced in the collection of secondary data too. In general, life-cycle databases and EPA AP-42 can be used to supplement primary data.

4.2.5 Data Validation

According to ISO 14044 (ISO 2006b), validation of data is the first step in the data calculation task. The data collected should be validated to confirm compatibility with system boundaries and data-quality requirements for the intended application. Validation can involve system boundary verification if data from literature sources are used, and checking mass balances, energy balances or comparative analyses of inventory items against other sources. Benchmarking is commonly used in the validation of collected and calculated inventory inputs and outputs. The calculated inventory data are compared against inventory data in the literature for reasonableness. The primary objective of benchmarking is to check the reasonableness of the calculated inventory but, in doing so, it is important that the system boundary of the compared inventory be consistent. The assumptions and limitations of the comparison can be clearly discussed in the inventory report.

4.2.6 Data Aggregation

Typically, each product or service in a pavement LCA is composed of multiple unit processes. Inventory data are generally collected for individual unit processes and need to be aggregated to describe supply chains and production streams.

Major steps to aggregate unit processes are as follows:

1. Identify unit processes contributing to the process based on the system boundary defined for the material.
2. Determine proportions of each unit process contributing to the aggregated process (e.g., 0.107 kg coal, 1.37 kg limestone, 0.144 kWh electricity, etc. to produce 1 kg cement). These proportions should be determined as part (step 2) of the initial data-collection stage for primary and secondary data.
3. Aggregate individual unit processes with the proportions identified in the previous step to define aggregate inputs and outputs per a reference unit (usually defined per unit mass or volume of production at this stage).
4. Store the aggregated data for each life-cycle stage separately for further reporting and breakdown of LCA results.

4.2.7 Translate Data to Unit Processes and Functional Unit

This is the step where the inventory data collected for unit processes are aggregated to calculate inventory inputs and outputs that are related to the functional unit chosen in the goal and scope phase. This should be done for the data collected for each life-cycle stage. The procedures may differ for each life-cycle stage. An appropriate reference flow for the materials-production stage and other stages requires input from the materials-production stage (e.g., maintenance and rehabilitation and some components of the use stage) and should be determined for each unit process, as this is necessary to fulfill the function quantified by the functional unit. The quantitative input and output data of the unit processes are calculated in relation to this flow. Based on the flow chart and the flows between unit processes, the flows of all unit processes are related to the functional unit.

The data collected as a result of use-stage components and construction activities are generally for the entire project and should be translated to the functional unit if needed.

4.2.8 Allocation for Flows and Releases

According to ISO 14044, allocation is 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 2006b). ISO 14044 recommends avoiding allocation when possible and offers several options for doing so. Unfortunately, the reality of performing LCA is such that allocation is often unavoidable.

In most pavement LCA studies, the boundaries for the system of production are often crossed and, thus, allocation is necessary. Allocation is relevant in the following three situations:

1. **Multi-Output Situations.** Some manufacturing processes with co-products (e.g., oil refineries and the asphalt-binder-production process) and processes or systems used by multiple products (e.g., transport of multiple goods and raw materials) are considered in this category. The allocation options for such processes are summarized in figure 4-5 with the allocation decision matrix. ISO advocates avoiding allocation, when possible, by dividing the system into its subprocesses (ISO 14044 and 14049 [2006b, 2006c]). Input and outputs are tracked at the process level, as opposed to an aggregated production level calculation. When individual subprocesses also produce multiple outputs, allocation must be applied at the subprocess level. 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; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. There can be many different underlying physical relationships but most options for pavement LCA are physical based (i.e. mass, energy) or economic based. A good example of physical-based allocation is the transportation unit process where multiple products can be hauled with the same transport unit. Inputs and outputs can be distributed to the products using the same transportation service based on either mass or volume, depending on which is most relevant. As a second allocation option where the physical relationship alone cannot be established or cannot be used as the basis for allocation, the products and functions should be allocated 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. Sometimes it is necessary to expand the system boundaries to include the additional functions related to the co-products to reflect the relationship between them properly.
2. **Reuse and Recycling Situations.** These situations can include the reuse of components and recycling of materials after initial use, such as steel rebar, reclaimed asphalt pavement, coal combustion co-products from power generation, or the use of discarded tires in asphalt binder. ISO recommends avoiding allocation for reuse and recycling situations by expanding the system boundaries (ISO 14044 and 14049 [2006b, 2006c]).

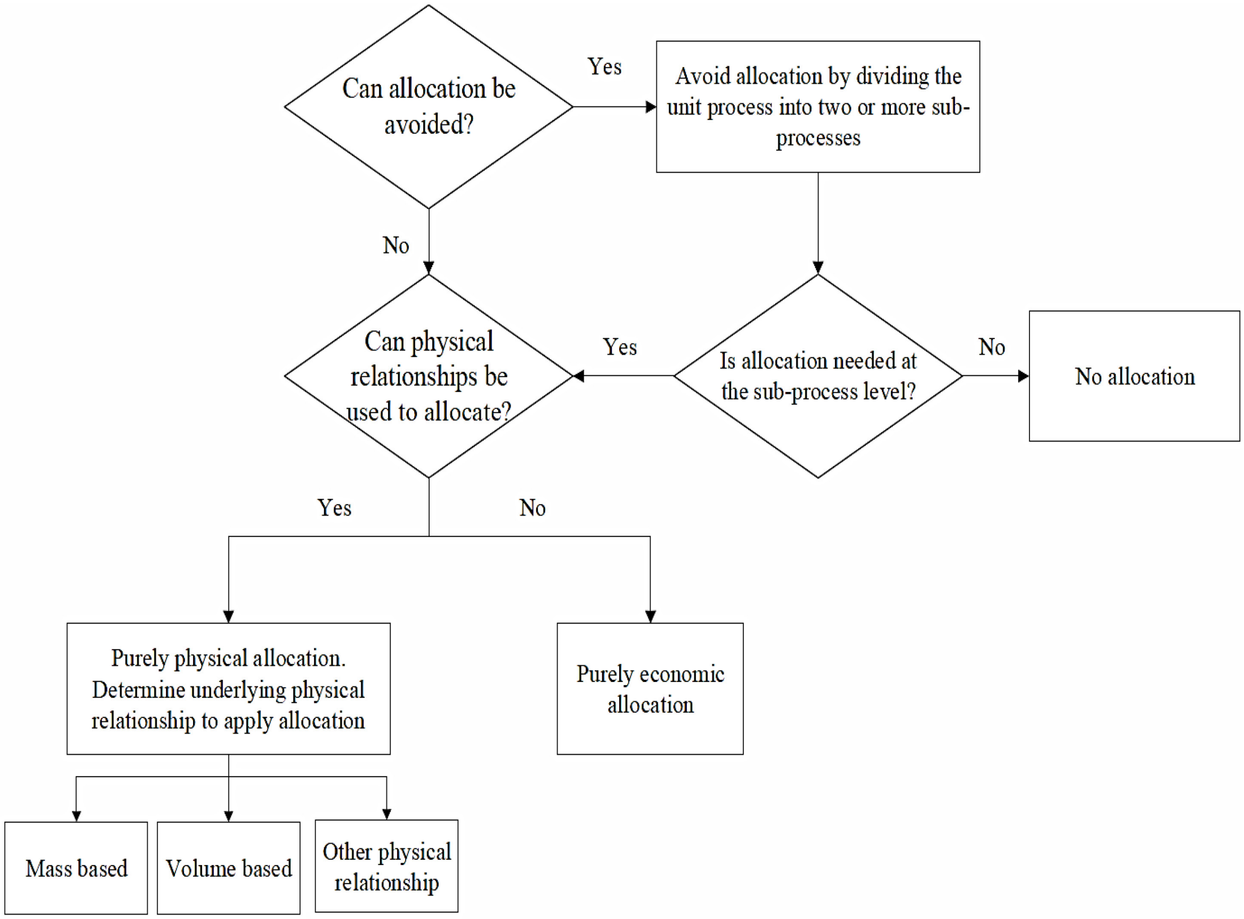


Figure 4-5. Allocation decision matrix for multi-output scenarios.

Several allocation rules and procedures are applicable to reuse and recycling. An important part of the terminology related to recycling is captured in ISO 14044 when it defines closed-loop recycling as being when a material from a product is recycled into the same product system, while defining the open loop as being when a material from one product system is recycled in a different product system. There are several allocation methods that are applied to reuse and recycling instances, some of which create a disconnect between different life cycles. Typically, a cutoff approach is followed where processing and handling up to a stockpile or storage is included, but the processes to be able to reuse the material are left for the next life cycle. This approach is typically applied in EPDs, as they generally focus on the life cycle of a specific product or application for a specific year.

Other LCA studies, and mostly studies that look at a broader policy or economy perspective, include what is referred to as a substitution method, where a credit is assigned to the life cycle under study as it allows for another use where the need for new extracted material is prevented. However, caution should be taken when doing so as this can lead to double counting of benefits. An example would be where both the life cycle that produces the recycled content, and the life cycle that is utilizing the recycling content take the same substitution credits.

A third option is the 50/50 method, in which half of the benefits of recycling are allocated to the pavement using recycled materials and the other half are allocated to the pavement producing the recyclable material. This approach is arbitrary and is not recommended for any type of pavement LCA.

3. **Multi-Input Situations.** Waste treatment processes, such as incineration and landfilling, are considered in this category. An example of allocation for landfilling would be to look at the chemical composition of the waste materials and the relation to the emissions to air and leaching from the landfill. Landfill models in Ecoinvent use these underlying relationship to assign inputs and outputs to different waste flows that enter the same landfilling process.

Some general guidance about allocation and its implementation is provided below.

- Approximate (as much as is possible) the fundamental input/output relationships and characteristics; in other words, 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.
- Where physical relationships alone cannot be established or cannot be used as the basis for allocation, allocate 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.
- Warrant that the sums of the allocated inputs and outputs of a unit process are equal to the sums of the inputs and outputs of the unit process before allocation, respectively.
- When several alternative allocation procedures seem applicable, conduct a sensitivity analysis as a way of illustrating the consequences of applying the alternative approaches.

Recycled, Co-Product, or Waste Materials. What's the Difference?

- *Recycled materials are obtained from an old pavement and included in materials to be used in the new pavement. Common recycled materials include reclaimed asphalt pavement or recycled concrete pavement. Depending on the regional market, these materials would be "waste" if not recycled, ending up in a landfill. Allocation of environmental impact between the manufacture of the original material and its recycling in the new material is based on the processing needed to make this material suitable for use in the new pavement. The demolition of the existing pavement and its transportation to a processing plant is allocated to the old pavement.*
- *Co-products are derived as part of another process, often industrial but possibly agricultural, that brings value to the overall process. For pavement applications, asphalt binder is considered a co-product.*
- *Wastes are materials that normally would be sent to a landfill, for which the cost of transport and processing is the only source of economic value. If the material has value beyond this, it is no longer considered a waste, but instead a co-product. Recycled asphalt shingles is an example of one such waste material as long as the economics stay consistent with the above definition. The classification of fly ash is more complex, as in some regional markets it would fit the definition of waste whereas in other markets it is clearly a co-product because it has economic value beyond the cost of transport and disposal.*

- Apply allocation procedures uniformly to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products leaving the system (e.g., intermediate or discarded products), then the allocation procedure should be similar to the allocation procedure used for such products entering the system.

ISO 14044 or 14049 offer some specific guidance on allocation as applied to reuse and recycling:

- Changes in the inherent properties of materials should be taken into account.
- Allocation for reuse and recycling needs to be consistently applied to warrant that allocation approach for the reuse and recycling outputs. In addition, the approach for the use of inputs from reuse and recycling must add up to 100 percent to avoid double counting or undercounting. A clear definition of the system boundary of the recovery processes between the original and subsequent product system is needed.

A general consensus among LCA practitioners and those involved in evaluating products and systems is that allocation rules should be set up to:

- Prevent double counting of credits or the omission of important items.
- Provide fairness between industries by reflecting as closely as possible what is actually happening.
- Be transparent so that all parties can understand how allocation is applied and how it influences the results.

4.2.9 Decision Rules and Refining System Boundaries

The material inputs and outputs to be included in the inventory analysis and system boundaries are finalized after the application of decision rules to the initial data collected. Applying decision rules and eliminating some of the material inputs and outputs using cutoff criteria allows greater focus on the materials that are considered significant in terms of their mass, energy, or environmental significance. This is an effort to optimize resources (time and cost) required for inventory analysis. Therefore, cutoff criteria for inclusion and exclusion of material input and outputs in any part of LCA are intended to support an efficient calculation procedure and data-collection process. Decision rules are applied to material and energy inputs and outputs as recommended in ISO 14049:2006c.

The following steps are used in applying decision rules:

1. Identify unit processes and aggregated processes or life-cycle stages to apply decision rules. These can be processes or stages with incomplete material input data.
2. Complete the data gaps in a conservative manner using other data sources and best estimates.
3. Apply cutoff rules to the initially collected, validated, translated and allocated data.
4. Perform sensitivity analyses using the three cutoff rules (i.e., mass, energy and environmental significance) so that all inputs and outputs cumulatively contributing more than a defined amount to the total are included.
5. Include or exclude materials from the unit or aggregated process or a life-cycle stage based on the cutoff criteria (e.g., percentage of total) agreed upon in the scoping phase.

6. Refine system boundaries and repeat steps 1 to 9 shown in figure 4-3 for any process affected by this.

The criteria adapted should be clearly documented. Reflecting the iterative nature of LCA, decisions regarding the data to be included can be based on a sensitivity analysis to determine their significance. A sensitivity analysis may help identify the need to revise the initial system boundary, or may identify other steps that may be needed to improve the analysis (e.g., exclusion of life-cycle stages or unit processes, exclusion of inputs and outputs for a specific unit process, or inclusion of new unit processes, inputs and outputs).

Several cutoff criteria are used in LCA practice, including mass, energy and environmental significance. A detailed description of various cutoff criteria is given in chapter 3. According to EN15084, the following recommendations should be followed for the exclusion and inclusion of inputs and outputs (CEN 2013):

- The first choice is the inclusion of all inputs and outputs associated with a unit process when the data are available. Data gaps may be filled with average or secondary data that can be obtained from other data sources or conservative assumptions based on engineering judgment. Any assumptions for such choices should be documented.
- If data for inputs are insufficient for a unit process, the cutoff criteria should be 1 percent of renewable and nonrenewable primary energy usage, or 1 percent of the total mass input of that unit process. The total of neglected inputs per major life-cycle stages cannot exceed 5 percent of the total energy usage or mass.
- Any decision made by mass balance should be supplemented by a criterion for environmental relevance. A quantitative decision rule for environmental relevance may be established for each individual data category or impact assessment category.

4.2.10 Data-Quality Assessment

The results of an LCA are a direct reflection of the quality of data used. Consequently, when conducting a pavement LCA, it is important that the "best available" sources should be used and existing standards and guidelines should be followed. Some of the available sources to perform pavement LCI and LCA are presented later in this chapter. However, existing guidelines (e.g., ISO 2006a; ISO 2006b; and Harvey et al. 2010) do not provide specific instructions on which data sources should be used. Therefore, an objective approach to data-quality assessment is required to:

- Check consistency and compatibility of used data with goals and scope of the study.
- Document the quality of the data source(s).
- Improve the credibility of the pavement LCA results.
- Perform sensitivity analysis using statistical methods.

According to ISO 14044, data quality is defined as "characteristics of data that relate to their ability to satisfy stated requirements" (ISO 2006b). To ensure comparable results and usefulness in future work, the same systematic requirements must be used to assess the data quality. ISO 14044 provides a series of requirements that can be used to assess data quality. This part of the framework follows the ISO requirements and provides more explanation and illustrations for each ISO requirement regarding pavement LCA to help users conduct data-quality assessment. Data quality focuses on "how representative" and "how accurate" those data are, and uses different quality indicators for both categories.

The data collection should aim to achieve the desired level of data quality documented in the goal and scope. It is recommended to assess the data quality for each unit process using data-quality indicators defined by ISO 14044 (ISO 2006b):

- Time-related coverage.
- Geographical coverage.
- Technology coverage.
- Precision.
- Completeness.
- Representativeness.
- Consistency.
- Reproducibility.

Primary data should adhere to the highest data quality to the extent that time and resources permit. Secondary data should aim to do the same, but it is understood that this is generally not possible.

The recommended steps for performing data-quality assessment are listed below.

1. **Develop a Data-Quality Scoring Criteria.** This is generally documented clearly in the goal and scope document. Even though there are some examples of this in the literature, the development of appropriate scoring criteria may be study dependent.
2. **Assess the Representativeness of Each Inventory Source Used in the Study.** The assessment should be based on the data-quality indicators determined in step 1 (discussed above). The same source may result in a different scoring subset for different applications. An inventory report can be produced that contains details of each inventory data source.
3. **Evaluate Data Quality of the Unit Processes.** In a comprehensive LCA, there may be hundreds and thousands of unit processes; therefore, it is not practical to conduct an evaluation for each unit process. Instead, this can be done for major unit processes and products that are commonly aggregated for multiple unit processes (e.g., Hot-Mix Asphalt (HMA) plant production, aggregate production, binder production, and cement production).
4. **Evaluate Data Quality of Aggregated Processes and Calculate an Overall Score for Major Processes**. The overall score reflecting the representativeness of major processes (e.g., cement manufacturing process, HMA plant production process, aggregate quarrying process, etc.) can be used in the sensitivity and uncertainty analysis.

A detailed discussion with examples for executing each step introduced above is provided in the commentary section of this chapter.

4.2.11 Documentation of Inventory Database

The final LCI database for each materials and life-cycle stage with the data sources, emission factors, and models, along with limitations and assumptions, should be transparently documented in an inventory report. A sample inventory-data template for materials is provided in figure 4-6.

<table>
<tr><td>Name</td><td colspan="6">(Type of material)</td></tr>
<tr><td>Used by the supplier/ contractor for:</td><td colspan="6">(How is the material being using in the pavement system?)</td></tr>
<tr><td>Description of use</td><td colspan="6">(Description of relation to pay items / LCA module(s))</td></tr>
<tr><td>Description of the actual supplier/ contractor supply chain</td><td colspan="6">(What actually happens and if we had primary data for it, that would be best)</td></tr>
<tr><td>Unit process</td><td colspan="6">(Description of processes, technology, volume etc. covered in the data, flow diagram if available)</td></tr>
<tr><td>Most relevant environmental impacts</td><td colspan="6">(Description of most relevant impacts and how they are modeling in this study)</td></tr>
<tr><td>Allocation</td><td colspan="6">(Description of any included allocation, if only for co-products and recycled content)</td></tr>
<tr><td>Major assumptions</td><td colspan="6">(Description)</td></tr>
<tr><td>Benchmarks</td><td colspan="6">(Lessons learned from benchmarks)</td></tr>
<tr><td>LCI Source</td><td>Reference(s):</td><td colspan="3">(Numbered list of references)</td><td>Type:</td><td>□ Unit process
□ Aggregated</td></tr>
<tr><td>Owner/ involved parties</td><td colspan="6">(Names of the company, association, members, ….)</td></tr>
<tr><td>Geography</td><td>□ Supplier/ Contactor</td><td>□ Statewide</td><td>□ US</td><td>□ Canada</td><td>□ Europe</td><td>□ Other</td></tr>
<tr><td rowspan="3">Data quality</td><td>Reliability</td><td>Completeness</td><td>Temporal correlation</td><td>Geographical Correlation</td><td>Technological Correlation</td><td>Sample Size</td></tr>
<tr><td>(description)</td><td>(description)</td><td>(description)</td><td>(description)</td><td>(description)</td><td>(description)</td></tr>
<tr><td>(number)</td><td>(number)</td><td>(number)</td><td>(number)</td><td>(number)</td><td>(number)</td></tr>
<tr><td>Meets desired data quality?</td><td>(1: yes/ 2: no)</td><td>(1: yes/ 2: no)</td><td>(1: yes/ 2: no)</td><td>(1: yes/ 2: no)</td><td>(1: yes/ 2: no)</td><td>(1: yes/ 2: no)</td></tr>
<tr><td>Completeness</td><td>Mass balance:</td><td colspan="2">□ yes (>99%wt.)
□ yes (>95%wt.)
□ no
□ Unknown</td><td>Energy balance:</td><td colspan="2">□ yes (>99%wt.)
□ yes (>95%wt.)
□ no
□ Unknown</td></tr>
</table>

Figure 4-6. Sample inventory-data template for materials.

4.3 Commentary

4.3.1 Data-Collection Preparation

Preparation for data collection includes identifying a list of materials and processes for data collection, developing flow diagrams for major materials to guide data collection, and preparing a plan for collecting data using the available sources and ensuring consistency with the data and data-quality requirements defined in the scoping phase.

The development of process flow diagrams for all major products or operations (which may consist of many underlying unit processes) can be useful in identifying the needed data and highlighting the major production steps to collect information. An example of a flow diagram is shown below in figure 4-7 for asphalt-binder production, which is an aggregate of unit processes. These processes include crude oil extraction, refining, and asphalt-binder blending and storage.

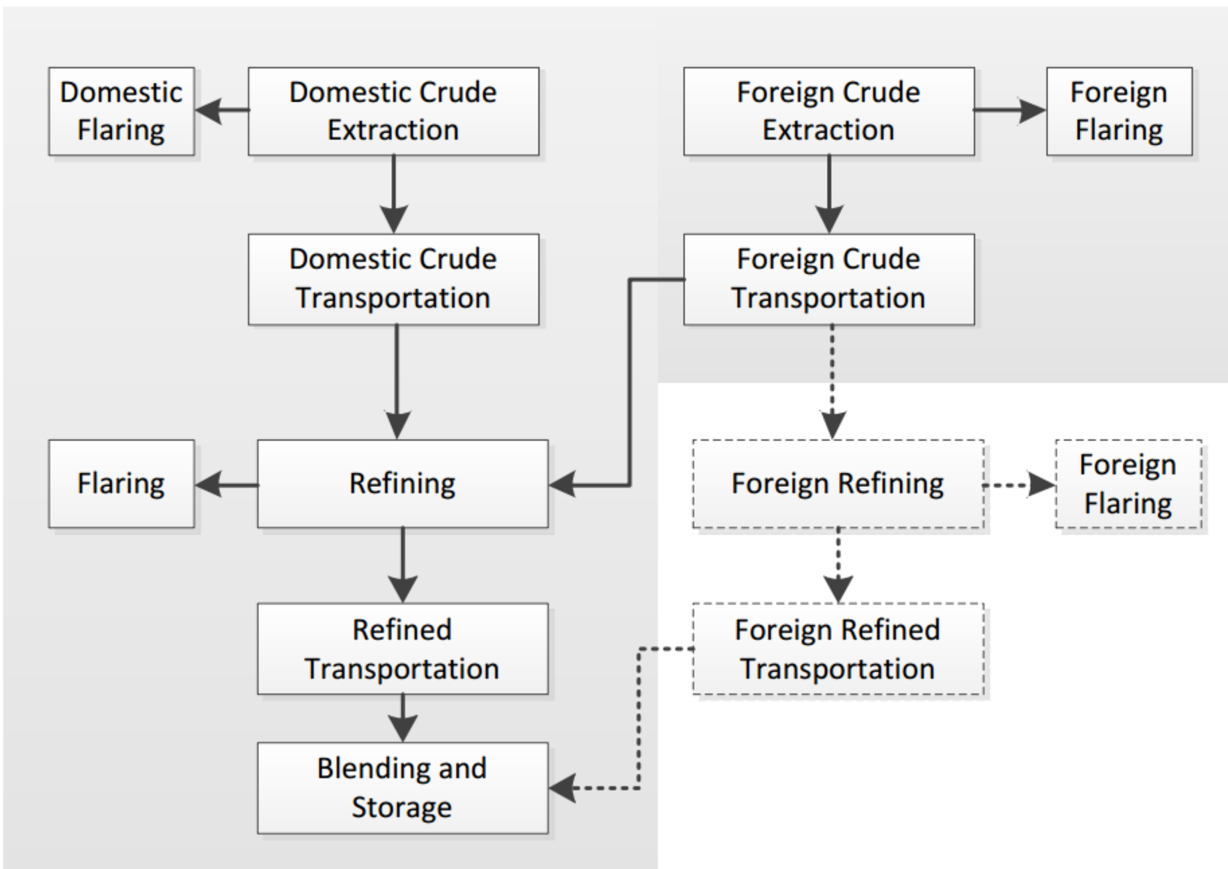


Figure 4-7. An example system boundary for asphalt-binder production (Yang 2014).

Each unit process contributing to the product or operations should be described in detail to avoid any misunderstanding of represented data. Different data-collection strategies can be developed for each unit process, depending on the data availability. One may collect a combination of primary and secondary data from different sources in the entire system boundary. If data for some unit processes inside the system boundary are not currently available, proxy data can be used. Documentation is needed to allow any future modification when data for unit processes are available.

Data-Collection Strategy for Concrete EPD

An example of a data-collection strategy is provided in a recent document (CLF 2013), which states that the preferred choice of data is prioritized as follows:

1. *Plant-specific primary data.*
2. *Company-weighted average data.*
3. *Regional-weighted average data.*
4. *ISO-compliant and reviewed LCI for used supplier.*
5. *Current industry average data supported by a published ISO-compliant LCA.*
6. *Default LCI sources updated by industry associations.*
7. *U.S. LCI Database (NREL 2015).*
8. *Other LCI sources (including, but not limited to, proprietary datasets, published research and economic input/output data) in which the technology and energy source mix reflects the in-use conditions.*

Data-collection steps may vary depending on the goal of the study, such as whether it is an initial screening or a comprehensive LCA. An average environmental LCA for a typical overlay (as compared to other pavement treatment methods) is considered initial screening, whereas detailed production and construction is part of a specific project LCA. Data-collection strategies may also exhibit some differences with respect to consideration of different life-cycle stages of pavements, such as materials, construction, use, and end of life. For example, the focus of data collection for the materials and production stage is inventory data collection for the production of pavements, whereas the data and models supporting vehicle-pavement interaction models are sought for the use stage. An example data-collection strategy is provided in the callout box for the development of concrete EPD.

The goals of the study and data-quality requirements, along with the available resources (time and money), affect decisions regarding data type choices and data-collection strategies. The reliability of the inventory data varies depending on the type of the data (primary or secondary) and the source of the data when secondary data are used. Primary data collected through continuous emission monitoring system are anticipated to be more reliable than secondary data (which can vary depending on the data calculation approach and sources used). Figure 4-8 depicts the relative costs and reliabilities associated with different data-collection approaches. Pavement LCA typically uses a combination of different sources, such as publicly available documents, commercial databases, and primary data collected through questionnaires. A summary of commonly used data-source categories and their potential uses are summarized in table 4-7.

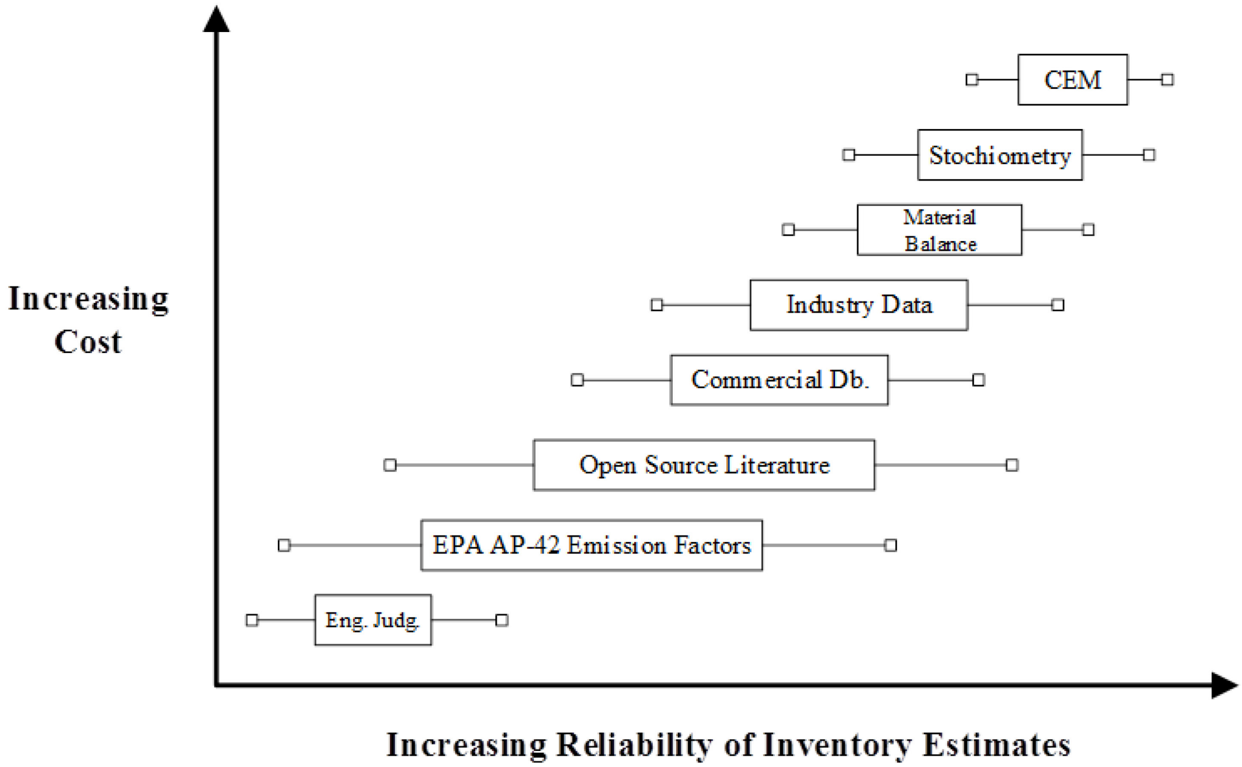


Figure 4-8. A comparison of reliability and cost estimates for various data-collection strategies (ranging from engineering judgment to continuous-emission measurements [CEM]) (after EPA 1995).

Table 4-7. Data-source categories and potential uses as primary or secondary data.

Source Category	Sources	Data Types	Publicly Available/ Critically Reviewed	Uses
Commercial	e.g., GaBi (Baitz et al. 2013) and Ecoinvent (Weidema and Hischier 2010)	Contains multiple databases including Europe- and U.S.-specific for a wide range of products and services.	No/Yes	Secondary data when needed for upstream, critical, and downstream processes and for models to support primary data
Public Databases	e.g., NREL (2015)	U.S. life-cycle inventory database covering commonly used materials, products, and processes in the U.S.	Yes/Yes	Commonly used as secondary data for upstream processes such as fuels and electricity.
EPDs (product specific)	e.g., Ready-mix concrete producers, asphalt mixture plant producers, aggregate suppliers, steel suppliers	Manufacturer-specific inventory databases	Yes and No/Yes	Primary data for a specific pavement material.
EPDs (industry -wide averages)	e.g., NRMCA (2014), ASTM (2015)	Industry-wide average inventory databases	Yes/Yes	Secondary data for a specific pavement material.
Industry Association Reports	e.g., PCA Reports (Marceau, Nisbet, and VanGeem 2006 and 2007)	Industry-sponsored studies to develop life-cycle inventory databases	Yes/No	Secondary data for specific pavement materials.
Governmental Databases and Reports	e.g., EPA MOVES (EPA 2014a) and EPA AP-42 (EPA 1995)	Air quality and greenhouse-gas emission database for major industries (not intended for LCAs)	Yes/No	Not a sole source for collection of primary or secondary data, but they can be used as supporting data as: 1. Secondary data 2. Emission factors with primary data collection
Scholarly Reports and Articles	e.g., Jullien et al. 2012, Korre and Durucan 2009	Research papers for a range of pavement materials and practices.	Yes/No	Not a sole source for collection of primary or secondary data. They can be used to support collection of secondary data.

Ecoinvent and Gabi are among the common sources for the raw material acquisition and production stage data. The unit processes existing in commercial databases can either be used directly as is or as a supplemental data-collection process providing emissions factors for many of the materials used in pavement construction.

Some specific sources for major pavement materials are presented in table 4-8. Various Portland Cement Association (PCA) inventory reports (Marceau, Nisbet, and Van Geem 2006; Nisbet and VanGeem 1997; Nisbet and VanGeem 2002; and Marceau, Nisbet, and VanGeem 2007) provide major documentation for the development of inventory models for concrete products as a source of secondary data. Eurobitume (2011) is major source commonly used for asphalt-binder production, even though data are prepared for northern Europe and may not be particularly relevant to North America; that report was developed following ISO 14040 and ISO 140444 standards and was subject to an external review. A widely used source for steel is the LCA report by the World Steel Association (World Steel 2011) that was used to develop a common worldwide methodology and LCI data. Despite the fact that aggregates are used in all pavement application in large quantities, there is not a comprehensive LCI database that can be used as a source of data and benchmarking for this material. Among the sources available, the WRAP model for LCA of aggregates (Korre and Durucan 2009) in the UK appears to be the only detailed inventory report prepared according to ISO guidelines.

Table 4-8. Summary of literature sources commonly used in developing pavement LCI (only data sources currently less than 10 years old are included).

Data-Collection Phase	Unit Processes	Data Sources (and Data from Models)
Materials and Production	Asphalt mixture production	Ecoinvent 3.1 (2016), Hot-mix asphalt plants emission assessment report (EPA 2009)
	Ready-mix concrete production	Ecoinvent 3.1 (2016), PCA (Marceau, Nisbet, and VanGeem 2006; Marceau, Nisbet, and VanGeem 2007)
	Asphalt-binder production	Ecoinvent 3.1 (2016, Eurobitume 2011)
	Portland cement manufacturing	Ecoinvent 3.1 (2016), PCA (Marceau, Nisbet, and VanGeem 2006)
	Steel manufacturing	World Steel 2011, Ecoinvent 3.1 (2016)
	Aggregate production	Crushed Stone Emission Factors chapter (EPA 2009), Sand and Gravel Processing Emission Factors chapter (EPA 2009), PCA (Marceau, Nisbet, and VanGeem 2007), WRAP 2009 (Korre and Durucan 2009, Jullien et al. 2012, Athena 2006, Häkkinen and Mäkelä 1996)
Construction	Equipment emissions and fuel use	NONROAD (EPA 2008b), CARB's OFFROAD (CARB 2007), NCHRP Report 744 (Skolnik, Brooks, and Oman 2013)
	Additional emissions/fuel due to traffic delay	MOVES (EPA 2014a), CARB's EMFAC (CARB 2006)
Use stage	Albedo impact on urban heat island and radiative forcing	Akbari, Menon, and Rosenfeld 2009, CARB 2013, Pomerantz, Rosado and Levinson 2015.
	Roughness/texture impact on vehicle fuel consumption	PIARC's HDM-4 model (Bennett and Greenwood 2003); Morosiuk, Riley, and Odoki 2004; Chatti and Zaabar 2012
	Structure response on vehicle fuel consumption	Pouget et al. 2012; Akbarian et al. 2012; and Chupin, Piau, and Chabot 2013
	Water pollution from leachate and runoff	IWEM (EPA 2002)
Transportation and Hauling	Hauling truck/Rail/Barge	MOVES (EPA 2014a), Ecoinvent 2.2 (Weidema and Hischier 2010), EPA/IPCC Emission factors (Eggleston et al. 2006), Emission Measurements from a Crude Oil Tanker at Sea (Agrawal et al. 2008), CARB's EMFAC model (Wang et al. 2012), CARB's OFFROAD model (Wang et al. 2012)
Fuels and Electricity	Fuel	GREET (Wang 2008; Wang 2013), Ecoinvent 2.2 (Weidema and Hischier 2010), NETL (Skone and Gerdes 2008), NONROAD (EPA 2008b)
	Electricity	Ecoinvent 2.2 (Weidema and Hischier 2010), eGRID (EPA 2015)

GREET (Keoleian et al. 2012; Wang 2013) is an open-access, spreadsheet-based software tool used to evaluate the impact of fuel use in transportation. The GREET model includes all fuel production processes from oil exploration to fuel use by vehicles, and also contains information on the shares of combustion processes and process fuels for each stage of fuel production.

The most commonly used sources for upstream energy and emissions of electricity are Ecoinvent (2016) and eGRID (EPA 2015). The eGRID provides a regional database for electricity production with fuel resource mixes and five major emissions (CO_2, CH_4, N_2O, NO_x, and SO_2). The eGRID database is often used as an input to develop regionalized inventory models for electricity production for different regions in the U.S.

MOVES (EPA 2014a) is an open-source software for transportation. A default database containing national data and factors to estimate regional data for 3,222 counties in the U.S. has been built into the MOVES model. MOVES is capable of estimating a wide variety of emissions and its framework is flexible, with many input and output options. It is commonly used to estimate transportation intensity for hauling raw materials to the plants and vehicle emissions during the use stage. The additional emissions and energy resulting from work zone traffic delays can also be computed by MOVES. The types of information MOVES needs include: vehicle type and percentage in total traffic volume, spatial and temporal speed distribution (coming from traffic simulator), road geometry and capacity, geography, and climate.

EPA's NONROAD software (EPA 2008) is commonly used for calculating energy consumption and emission rates for construction equipment, while fuel factors are provided by Skolnik, Brooks, and Oman (2013). CARB's OFFROAD is a similar program (CARB 2007).

The general assumption is to model the environmental impacts over 100 years. This is relevant for the end-of-life processes (landfilling in particular), and the life-cycle impact assessment for the global warming and ozone layer depletion impact categories. More detailed information on that topic is provided in chapter 3.

4.3.2 Initial Data Collection for Materials-Production Stage

According to EN15804 (CEN 2013), as a general rule, primary data derived from specific production processes or average data derived from specific production processes should be the first choice. When primary data are not available, other sources can be used with clear referencing and documentation (CEN 2013). In addition, the following are considered important:

- An average product needs to use representative average data for the production processes (e.g., average plant production of asphalt mixture from available estimated or measured data).
- A specific product needs to use primary data for at least the processes over which the producer has influence or control. For example, concrete mixture production in a ready-mix plant or asphalt mixture production in an asphalt plant both fall into this category. When primary data are not available or not accessible, secondary data can also be used if they are consistent with the data-quality requirements.
- Secondary data can be used for the processes when the producer does not have an influence. Examples include processes dealing with the production of input commodities (e.g., pavement markings and polymer modifiers), and ancillary materials used in the production of concrete (e.g., raw material extraction or electricity generation, often

referred to as upstream data). Inventory data for the production of diesel, natural gas, or electricity may also be generic (e.g., 144.0 MJ energy consumed and 1.04 kg of CO_2 released per production of 1 gal diesel or 14.1 MJ of energy and 1.03 kg of CO_2 released per production of 1 kWh of electricity). The same upstream processes may also include cement manufacturing, binder production at refineries, aggregate quarrying, crushing and screening, etc. Depending on the goals and scope of the study and available resources (time and money), primary or secondary data can be acceptable for these processes.

- Secondary data can be used for downstream processes, such as demolition and landfilling.
- Documentation of technological, geographical and temporal characteristics of secondary data should be included. This information is needed to justify the selection of data for a specific unit process.

Downstream and Upstream Processes

Upstream processes for materials in a pavement LCA typically refer to the processes associated with the extraction of raw materials used in the production. From the perspective of a pavement construction process, limestone quarrying, crude oil extraction, and polymer manufacturing can be considered as upstream processes. In general, secondary data are acceptable for such upstream processes. However, depending on the goals of the study and available resources, primary data can also be targeted for some upstream processes. For example, aggregate quarrying operations could be the focus of a pavement LCA where specific inventory data are collected from quarries (Jullien et al. 2012). The separation of upstream and downstream processes for the pavement LCA phases previously shown in figure 4-1 is cataloged in table 4-9.

Table 4-9. Pavement LCA application scenarios and corresponding variations in the focus (referring to the life-cycle blocks introduced in figure 4-1).

LCA Application	Upstream Processes	Downstream Processes	Processes Under Control of Initiating Party
Comparative assessment between rehabilitation types (e.g., in-place recycling vs. conventional overlays)	O-A-B[1]	D-E	C
Generation of an EPD to characterize resource flows for asphalt mixture or concrete (e.g., concrete, asphalt mixture)	O-A	C-D-E	B
Generation of an EPD to characterize resource flows for pavement raw materials (e.g., cement, aggregates, binder)	O	B-C-D-E	A
Project or network level assessment of road roughness on vehicle operations	O-A-B-C	E	D

1 Life-cycle stages are defined in figure 4-1 as A: Raw material acquisition, B: Materials Production, C: Construction, D: Use stage, E: End of life, O: Fuels and electricity production

Upstream processes also include production of fuels and electricity used in the other upstream and downstream processes that are directly related to the production of the studied product. In general, secondary data are acceptable for fuel and electricity production. However, there are some applications where more primary data can be used for fuel and electricity production. For example, regionalized inventory development (at the state or regional level) can include improving geographical and temporal representativeness of electricity production by collecting more primary data from electricity production available in eGRID (EPA 2015).

A fuel type's life-cycle energy and emissions input/output are categorized into upstream (energy required to extract, process, transport, refine/upgrade, and transport again to the point of combustion) and downstream (combustion in stationary and moving engines) processes. Similar to fuel, the life-cycle energy and emissions of electricity also consist of upstream and downstream processes. Energy consumption and emissions due to fuels and electricity used in plant operations and transportation of raw materials constitute direct energy usage and corresponding emissions. Energy and emissions associated with the production of fuels and electricity constitute indirect energy usage and emissions (upstream).

Downstream processes for the pavement life cycle generally include the processes that may take place during the construction and service life of pavements (construction, use, and end-of-life stages). These processes typically include fuel combustion in moving vehicles, including construction equipment and all types of vehicles using the pavement during its service life. Since it is almost impossible to obtain specific inventory data for those future processes, secondary data are used in the downstream processes. As primary data becomes available regarding some of the activities in these life-cycle stages, secondary data can be improved to reflect those specific processes. Downstream processes are typically modeled using scenarios for what most likely will happen.

Primary Data Collection

Examples of typical process-activity data to be collected from a plant to understand and quantify energy resources and seasonal variations include:

- Fuel type.
- Month.
- Units.
- Combustion type.
- Purpose.
- Total Production.
- Average Daily Production.

Typical primary data collected for the production of 1 ton of asphalt mixture and 1 m^3 of concrete are shown in table 4-10. The data in the table include raw materials and energy inputs required in the target unit process. In a ready-mix concrete plant, emissions related to concrete production are generally limited to dust and combustion of diesel in vehicles, which can be added to output flows using emission factors. Specific plant emissions should be added to the output flows for HMA plants as they are recorded as part of the permitting process.

Table 4-10. Example inventory data collected and calculated for production of typical asphalt and ready-mix concrete at their corresponding reference unit (data source: Ecoinvent).

Data Type	Inputs per Production of 1 Cubic Yard of Concrete[1]	Amount	Unit	Inputs per Production of 1 Short Ton of Asphalt Concrete[2]	Amount	Unit
Raw Materials	Portland cement	208.7	Kg	Asphalt binder	43.5	Kg
	Coarse aggregate	840.1	Kg	Coarse aggregate	444.5	Kg
	Fine aggregate	543.9	Kg	Fine aggregate	73.5	Kg
	Fly ash	52.2	Kg	RAP	345.6	Kg
	Tap water	93.4	Kg			
Fuel and Electricity	Diesel	131.9	MJ	Diesel	20	MJ
	Coal	615	MJ	Refining gas	62	MJ
	Petroleum coke	291.1	MJ	Naphtha	80	MJ
	Heavy fuel oil	9.1	MJ	Natural gas	322	MJ
	Light fuel oil	7.1	MJ			
	Electricity	546.2	MJ	Electricity	107	MJ
Transportation	Rail	6.82	Tkm	Rail	7.58	Tkm
	Lorry 20-28t	9.44	Tkm	Lorry 20-28t	3.49	Tkm
	Lorry 3.5-20t	0.998	Tkm	Van < 3.5t	3.15	Tkm
	Barge	49.2	Tkm	Lorry > 16t	1.26	Tkm
Waste	Disposal concrete, to landfill	17	Kg	Disposal asphalt mixture, to landfill	9	Kg

1 Inventory results are from "Ready-Mix Concrete, normal, at plant/US* US-EI U"
2 Inventory results are from "Dense-Graded Hot-Mix Asphalt, at plant/US* US-EI U"

Secondary Data Collection

Examples of secondary data include electricity production using coal in the life-cycle databases, diesel production at the refinery, and hauling transportation intensity. Depending on the goal and scope of the LCA, this may also include data for cement manufacturing and binder production.

Secondary data are generally collected for upstream processing, including fuels and electricity. Depending on the data-quality requirements, the data collected for fuels and electricity can be improved to meet quality requirements. The approach to develop fuels and electricity inventory data should be chosen to be consistent with the goals and scope of the LCA performed.

There are two commonly used approaches in developing LCI database for fuels and electricity. The first approach is to use existing commercially and publicly available databases such as US-EI (EarthShift 2013), eGRID (EPA 2015), or GREET (Wang 2013). Most of the publicly available, open inventory databases are not developed as life-cycle databases and they are commonly used for secondary average data or for single point impact categorization, including global-warming potential and energy consumption, respectively. Commercial life-cycle databases such as GaBi (Baitz et al. 2013) or US-Ecoinvent (2016) can provide a comprehensive list of inventory analysis needed for complete impact categorization for average U.S. fuel and electricity production. When the available literature data do not meet data-quality requirements, secondary data can be modified to meet data and data-quality requirements. The improvements can be done for two specific objectives: 1) to complete the inputs and outputs for calculating the required impact categories when publicly available data do not contain a complete list of emission substances to calculate required impact categories, and 2) to improve data quality by increasing its geographical and time-related representativeness.

A second approach can be used to improve the representativeness of fuel and electricity inventory databases, and requires the collection of production- and transportation-related data for fuels and electricity. In the case of fuels from petroleum, the following data need to be collected relevant to the production stages of fuels, including crude oil extraction, transportation, refining, and transportation:

- Crude oil distribution to the specific region; the Energy Information Administration (EIA) regularly publishes open source data about foreign and domestic crude oil production, imports, and movement (EIA 2013).
- Flaring data during crude oil extraction.
- Crude oil transportation data to estimate distances between source and regional refinery points with the method of shipment.
- Refined product transportation to blending terminals for asphalt binder or storage areas for distribution.
- Regional and most recent electricity production and resources used in the production of electricity transportation.

The additional data for electricity can be limited to the most recent resource mixes used in different regions of the U.S. to produce electricity. These may be adjusted if they are expected to change over longer analysis periods.

An example of a geographically more representative data collection for fuel production in the U.S. is shown in figure 4-9. The data-collection steps were followed for the life cycle of diesel to develop a regional secondary database.

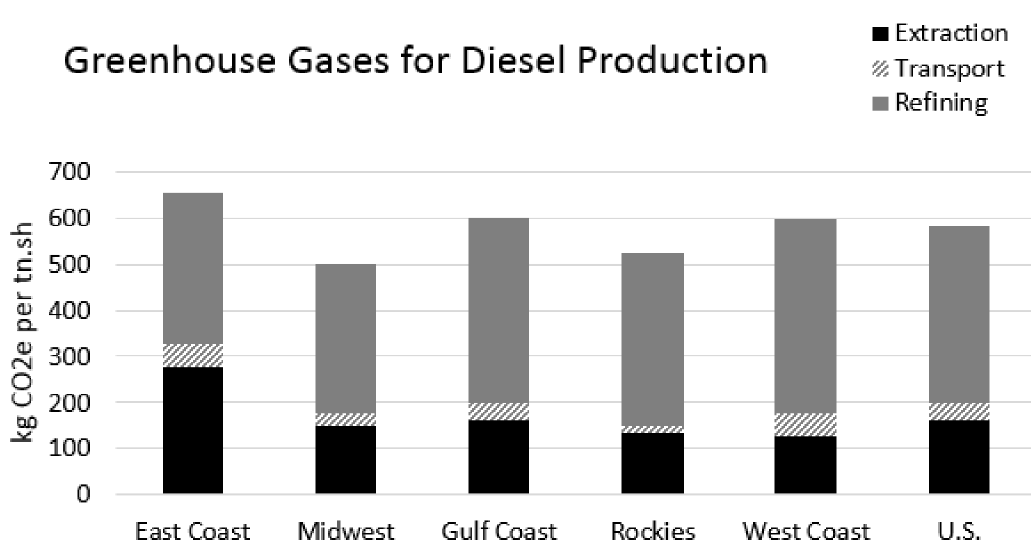


Figure 4-9. Greenhouse-gas emissions for diesel production in different regions of the U.S., illustrating the importance of using regional data for LCA (courtesy of UIUC).

When secondary data are used, they should be appropriately referenced as with any other source. As an example, the NREL LCI database explicitly suggests the following referencing style for use of its data modules:

> U.S. Life-Cycle Inventory Database. (2015). National Renewable Energy Laboratory, 2015. Accessed March 01, 2015: https://www.lcacommons.gov/nrel/search

This is the minimum level of referencing that should be provided. Additional details and references are required for specific unit processes used as part of the development of inventory. For example, the name of the unit process should be explicitly noted in the reference:

> U.S. Life-Cycle Inventory Database. Portland cement, at plant unit process (2015). National Renewable Energy Laboratory, 2015. Accessed March 01, 2015: https://www.lcacommons.gov/nrel/search

4.3.3 Initial Data Collection for Other Life-Cycle Stages

Data collection for the maintenance/rehabilitation and end-of-life stages is explained in detail the first part of this chapter. Further explanation of the construction and uses stages data collection follows.

Data Collection for the Construction Stage

The data collected for each type of construction activity includes equipment type and quantity and productivity (e.g., cubic yard per hour, tons per hour, linear feet per hour, etc.). An example of collected data for various construction activities is shown in table 4-11. This information is used to calculate emissions resulting from each construction activity using the emission factors and similar steps described in the calculation of outputs for primary and secondary data.

Table 4-11. Example selection of typical construction and inventory data collected for typical construction activities (UIUC 2015).

Task	Type	Productivity (units/hr)	Units	Equipment Type [number required]	Fuel Use (gal/hr)
Excavation	Earthwork	325	Cubic Yard	Roller - Soil [1]	5.40
				Dozer [1]	4.90
				Loader - R/T [1]	5.60
				Dozer [1]	4.90
				Truck - Water [1]	5.50
HMA - Surface Course	Paving	150	Short Ton	Truck - Distributor [1]	3.50
				Roller [1]	4.10
Asphalt Pavement Removal	Removal	50.0	Cubic Yard	Milling Machine [1]	19.8
				Broom [1]	2.30

The emissions from construction activities are primarily generated from burning fossil fuels such as gasoline, diesel, and liquefied petroleum gas (LPG) by construction vehicles. Process-activity data gathered for various construction equipment are used to calculate inventory results using appropriate emission factors. Figure 4-10 illustrates the calculation procedure. The emission factors used to calculate direct emission are usually coming from commercial life-cycle databases (Ecoinvent 2016) or EPA sources (EPA 2008a; EPA 2014a). A similar approach may be used for the maintenance and rehabilitation stage data collection.

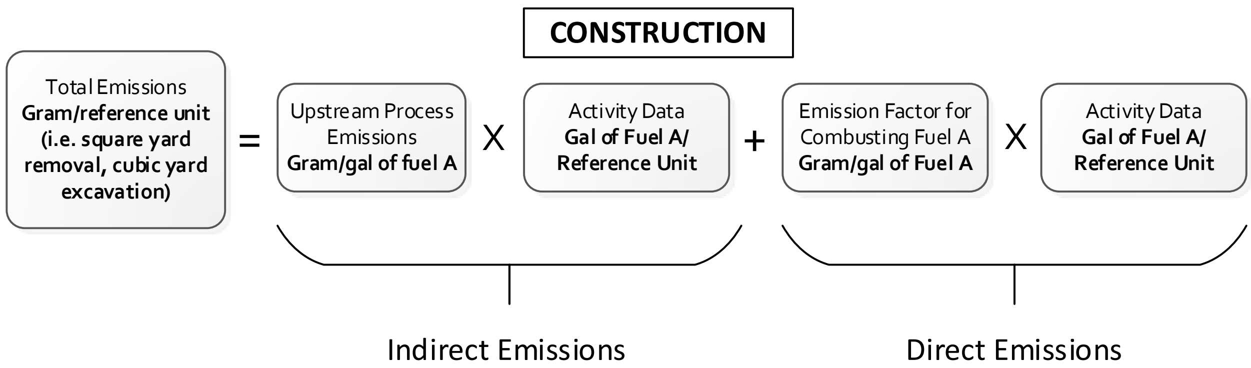


Figure 4-10. Calculation of construction-related emissions.

Data Collection in the Maintenance and Rehabilitation Stage

Data collection in the maintenance and rehabilitation stages can use different approaches to obtain the required information. One approach is the collection of performance data including historical progression of overall condition index, IRI, and texture to predict service life and develop a maintenance and rehabilitation schedule. A second approach is the gathering of maintenance and rehabilitation scheduled plans.

The maintenance and rehabilitation planning report includes the scheduled activities for specific pavement types. An example of various treatments scheduled for a continuously reinforced concrete pavement is shown in table 4-12.

Table 4-12. Recommended maintenance, preservation, and rehabilitation treatment cycle for a continuously reinforced concrete pavement (Illinois Tollway 2015).

Activity Type	Pavement Life (years)	Recommended Treatment for Roadway Lanes	Recommended Treatment for Shoulders	Inventory Requirement
Preserve #1	10	Patching	Rout and seal cracks Microsurface	Material and construction inventory
Preserve #2	17	n/a	Rout and seal cracks Microsurface	Material and construction inventory
Preserve #3	25	Patch; diamond grind surface	Patch Mill and overlay 2 inch	Material and construction inventory
Rehabilitation #1	33	Patch HMA overlay 4 inch	Remove rumble strips HMA overlay 4 inch	Material, construction, post-performance prediction (IRI and condition index)
Preserve #4	40	Rout and seal cracks	Rout and seal cracks	Material and construction inventory
Rehabilitation #2	48	Patch Mill and overlay 4 inch	Rout and seal cracks Microsurface	Material and construction inventory
Preserve #5	55	Rout and seal cracks	Rout and seal cracks	Material and construction inventory
Rehabilitation #3	63	Patch Mill and overlay 4 inch	Rout and seal cracks Microsurface	Material, construction, post-performance prediction (IRI and condition index)
Preserve #6	70	Rout and seal cracks	Rout and seal cracks	Material and construction inventory

Data Collection in the Use Stage

Once the use-stage components are determined for the LCA, an appropriate modeling approach is required to populate inventory inputs and outputs. Similar to the emission factors used in other stages, these models describe the relationship between activity data and energy consumption and environmental emissions. For example, activity data for the use stage may consist of vehicle operations (type, amount, growth, speed, etc.) and rolling resistance parameters for the pavement. Once the vehicle operations and rolling resistance parameters are known, emission factors can be used to calculate emissions and energy consumption due to pavement properties. However, many pavement characteristics that affect rolling resistance change with time as the pavement deteriorates and is maintained; therefore, these calculations must be repeated with evolving pavement and traffic parameters every year. Hence, the development of appropriate performance models will be needed as discussed in the previous section with the data collection for maintenance and rehabilitation stage.

Use-stage components define the relationship between pavement characteristics and impact on the environment as shown schematically in figure 4-11. The following sections discuss some of the critical use-stage components and their consideration in an LCA.

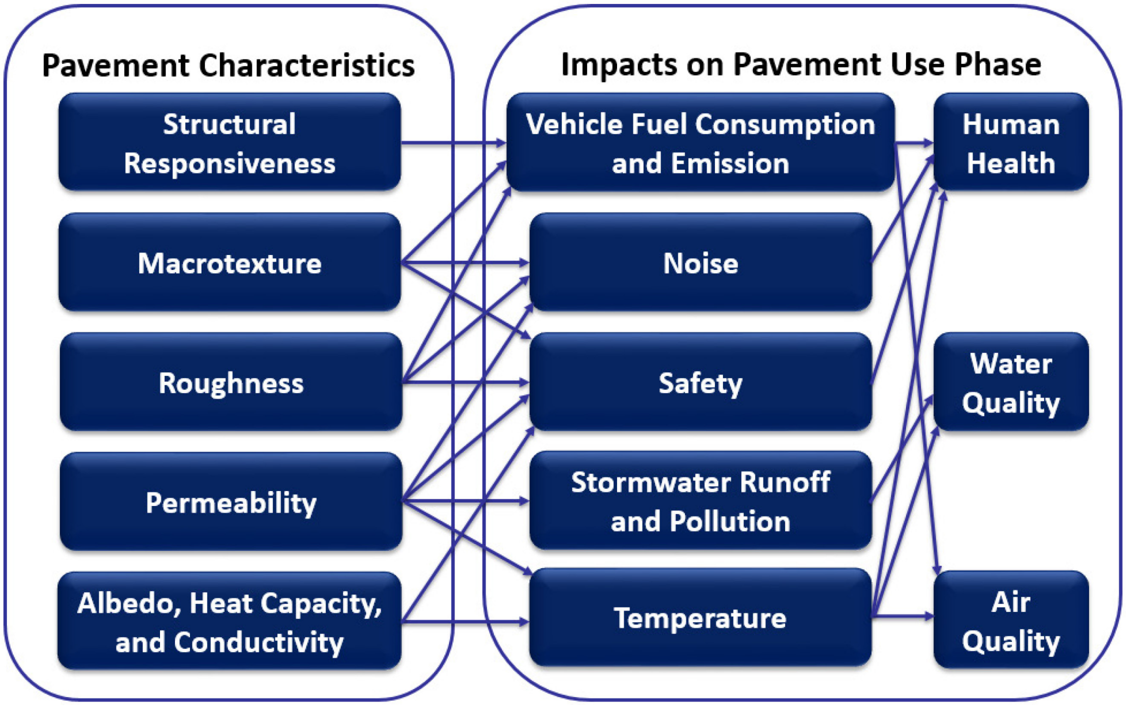


Figure 4-11. Pavement characteristics and influences on use-stage objectives (Van Dam et al. 2015).

Vehicle Fuel Consumption

Data collected for the use stage can be limited to models used to estimate the interaction between different pavement types, vehicles, and environment. As mentioned in the guidance part of this chapter, the three driving mechanisms resulting in pavement-related rolling resistance are roughness, texture (both of which require progression IRI and macrotexture over the analysis period), and structural response. An example procedure to calculate inventory outputs related to roughness and texture progression illustrated in figure 4-12. The illustrated procedure follows the step-by-step guidelines provided in the previous sections. Some of the critical steps to perform use-stage calculations are as follows:

- Pavement Segment: Determine pavement segment to be analyzed along with relevant input parameters as described in figure 4.11 (pavement type, length of section, roadway classification, geometric features, etc.)
- Traffic Model: Gather traffic data with vehicle distribution and percentages, vehicle types, and growth factor. The traffic modelling should provide traffic flow at a desired resolution if variable speed option is used in the analysis. Traffic loading data may be used as an input for pavement deterioration and IRI progression.
- IRI and Texture Progression: IRI and texture progression is estimated for the pavement segment. Progression curves should include the analysis period and any treatment activities affecting IRI and texture. IRI and MPD progression can also be expressed in terms of traffic input parameters.
- Pavement Rolling Resistance: The effect of IRI and texture can be integrated into vehicle specific power models such as in MOVES and HDM-4 as an additional rolling resistance term (Wang et al. 2012, Ghosh et al. 2015).

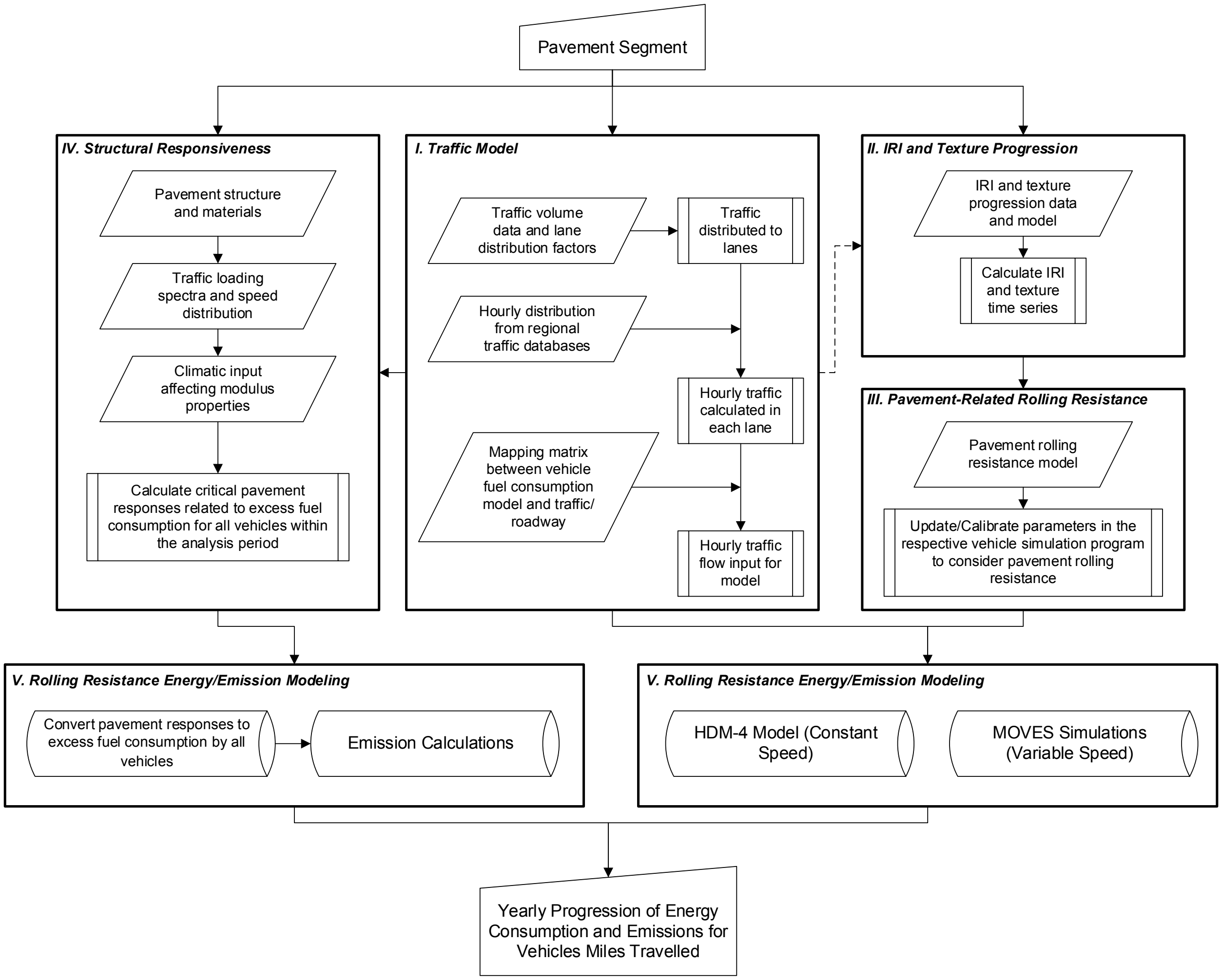


Figure 4-12. Procedures adopted by UCPRC to calculate use-stage inventory input-outputs for vehicle-pavement interaction (adapted from Wang et al. 2012).

- Structural Responsiveness: Pavement simulations are used to predict critical pavement responses related to excess fuel consumption of vehicles due to pavement deformations. Simulations, at a minimum, should consider traffic flow, traffic loading spectra, vehicular speed distribution, and climatic variations affecting pavement material properties. The outcome should be excess fuel consumed per vehicles mile travelled. Fuel consumption can then be converted to emissions using appropriate emission factors.
- Rolling Resistance Energy/Emissions Modeling: Vehicle emissions simulations are used to estimate excess emissions corresponding to roughness and texture progression data. EPA's MOVES program is commonly used to perform emission simulations due to roughness and texture. In order to convert excess fuel use due to structural response, EPA emissions factors (EPA 2008a) or some of the unit process related to mobile combustion sources available in commercial inventory databases can be used.
- Yearly progression of energy consumption and emissions are recorded per vehicles miles travelled.
- Based on use-stage calculations in comparing various rehabilitation methods, figure 4-13 shows the effect of IRI changes on fuel consumption and GHG emissions due to surface

treatment alternatives. The example demonstrates the impact of smoothness and traffic factors (growth percentage and fuel economy) on pavement-related fuel consumption for the first five years after treatment. The most significant reduction in fuel use comes from fewer vehicles travelling (3 percent vs. 0 percent traffic growth), especially for the zero growth rate assumption after construction. A smoother pavement after rehabilitation can reduce the annual energy consumption by about 2 percent compared with constructing smooth pavements.

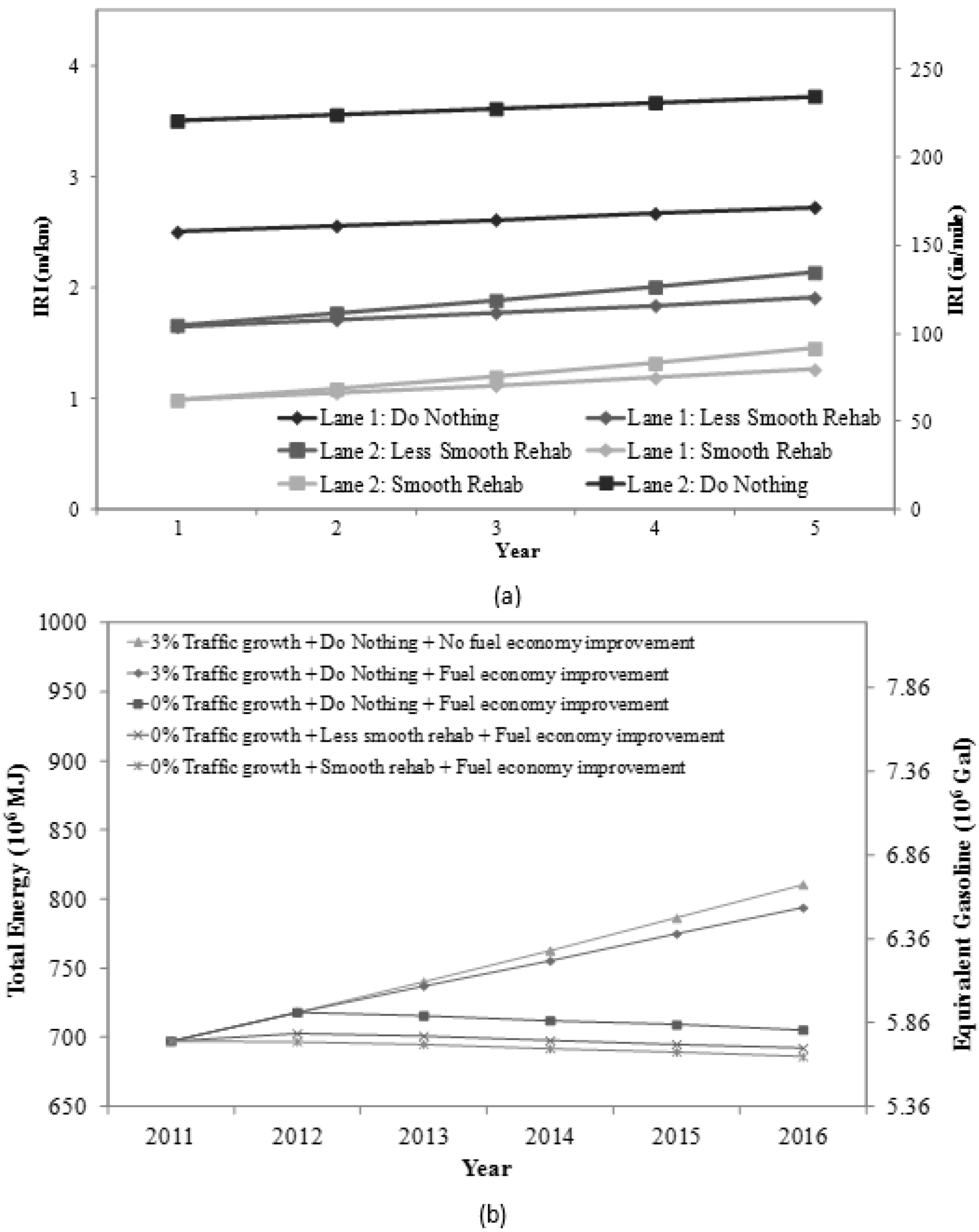


Figure 4-13. (a) IRI progression for various rehabilitation scenarios, (b) Corresponding additional energy consumption for each scenario (Wang et al. 2012).

Roughness and texture related fuel consumption calculations should be made by considering incremental changes in energy consumption and emissions with respect to a reference level of roughness and texture values. Reference values can be taken as the best possible roughness or texture that can be achieved in the region, or improvements in roughness can be compared with the current levels. In a comparative LCA, the reference value can be taken as the smallest original value. The inventory outputs are found by calculating the additional fuel consumption from a reference value and allows differentiation of two pavement surfaces (pavements A and B) with similar progression rate but at different levels of roughness as illustrated in figure 4-14.

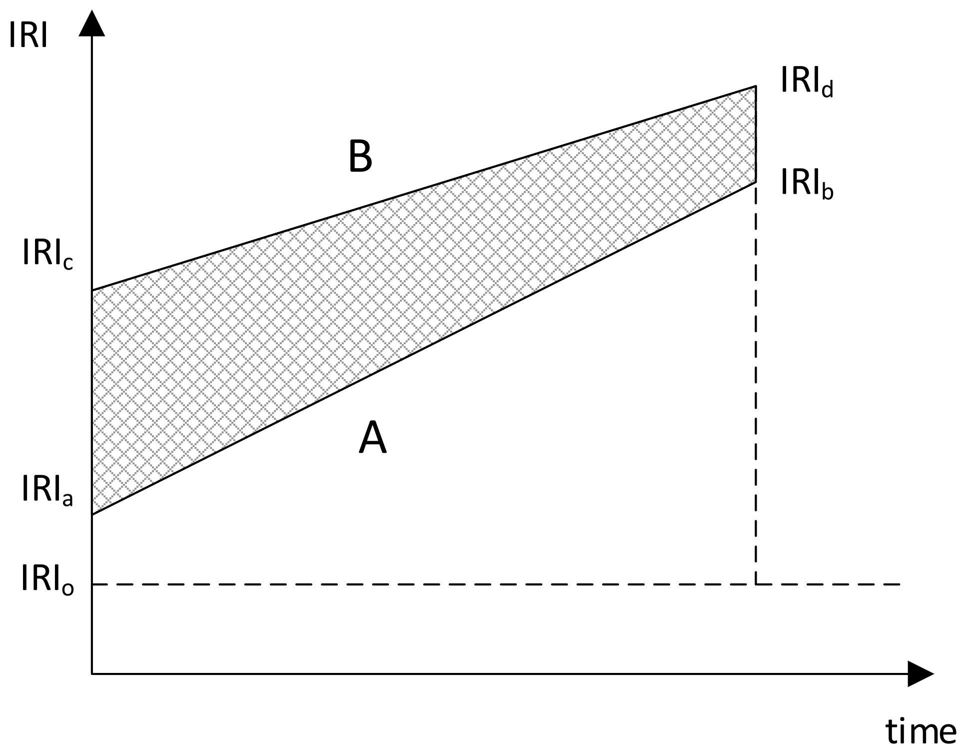


Figure 4-14. IRI progression of two pavement surfaces with the incremental changes illustrated with respect to a reference IRI (IRI_o).

When there are jumps in the progression models for IRI and texture due to rehabilitation activities, incremental changes should be calculated with respect to the values after the treatment.

Traffic volume and vehicle type distributions are key components of vehicle fuel consumption calculations. Traffic input data will determine the volume of traffic (current and future growth) and its distribution to different types of vehicles daily (peak or off-peak hours), weekly (weekends and weekdays), and monthly basis resulting in total vehicle miles travelling in a specific pavement section or over a network. Another important traffic characteristic to consider in the use stage is speed distribution for each vehicle considered. Vehicle speed has an interaction with the three pavement-related, rolling-resistance mechanisms. The three traffic scenarios, assumptions, and requirements are shown in table 4-13. The degree of accuracy required for the LCA should be determined in the goal and scope phase depending on the LCA application and data-quality requirement.

Table 4-13. Traffic scenario considerations for use-stage calculations and limitations.

Traffic Speed Scenario	Data Source	Commonly Used Rolling-Resistance, Energy-Emissions Model	Limitations
Steady-state speed	Posted or assumed speed	HDM-4 (PIARC 2002 and Chatti and Zaabar, 2012[2]) or MOVES[1] (EPA 2014a)	Ignores the effect of changing speed on vehicle-fuel consumption and likely to overestimate roughness-related rolling resistance when vehicles slow down due to congestion
Variable speed type A	State or Agency's Performance Measurement System	MOVES[1] (EPA 2014a)	The data is for current traffic volumes and capacity and ignores future changes in traffic and roadway capacity resulting in potential congestion-related speed changes.
Variable speed type B	Traffic Simulations Considering Roadway's Functional Features	MOVES[1] (EPA 2014a)	Require time consuming traffic simulations to come up with spatial and temporal distribution of speed to each vehicle group and can be prohibitive for network level applications.

1 MOVES program with modified parameters to consider pavement characteristics.
2 HDM-4 model is calibrated using field data (Chatti and Zaabar, 2012) at three discrete vehicle speeds. Due to lack of calibration for a wide variety of speeds, this model is commonly used with constant speed assumption.

The third component of vehicle fuel consumption is related to pavement-structural response and its effect on vehicle's rolling resistance and fuel consumption. It is a subject of ongoing research in the U.S and Europe. Up to 2014, a number of field studies have been performed to measure the effects of pavement type and structure on vehicle fuel economy, including those by Zaniewski et al. (1982), Taylor and Patten (2006), Ardekani and Sumitsawan (2010), Bienvenu and Jiao (2013), and Hultqvist (2013). These studies provide some insights into this phenomenon that may affect vehicle fuel consumption depending on the pavement type and structure. However, all of these studies provided only general descriptions of the pavement types, and none of these studies included mechanistic characterization of the pavement responses or modeling to be able to generalize the results with the result that the outcomes of these studies cannot be generalized for all pavement types and structures. Therefore, mechanistic-based approaches are required to assess the relationship between a pavement's structural response and the associated vehicle fuel consumption.

The additional rolling resistance due to a pavement's structural response has been characterized by two different approaches: dissipated energy approaches (Pouget et al. 2012; Chupin, Piau, and Chabot 2013) and pavement surface deflection-based methods (Akbarian et al. 2012; Loughalam, Akbarian, and Ulm 2013). It was also shown that theoretically these two methods may yield equivalent results (Loughalam, Akbarian, and Ulm 2014). Generally, finite element modeling tools are required to simulate the structural rolling resistance from the pavement-tire interaction, where tires are nonuniform and generate three-dimensional stresses. (Pouget et al. 2012, Chupin, Piau, and Chabotet 2013). Viscoelastic beam solutions have also been developed which provide faster solutions (Loughalam, Akbarian, and Ulm 2014). The results of any of these modeling approaches must consider changes in structural response caused by different traffic loads and speeds, and different pavement temperatures (asphalt materials) and moisture and freezing conditions (granular and soils materials). These effects on structural response and associated energy consumption should consider the distributions of all of these variables over time (hours of the day, month to month).

Consumption of energy due to pavement-structural response through viscoelastic deformation of asphalt pavement materials under vehicle loading was predicted for 17 field sections in California by using three different models employing different approaches (Coleri et al. 2016) and simulation of the distributions of traffic loads and speeds and pavement temperatures (Harvey, Lea, and Changmo 2016). These simulations showed that currently available models can produce similar trends but very different results. The modeling and simulations were performed as a first step towards calibration of the models considered in the study with field measurements of vehicle fuel economy on the modeled and sections and vehicles. In another effort, three-dimensional finite-element simulations with moving load, nonuniform and three-dimensional tire contact stresses, and dynamic analysis features were adopted using 4 method of dissipated power (Shakiba et al. 2016). The use of rate of external work to calculate pavements structure-related power dissipation allows applicability of finite element modeling for the analytical framework provided by of Chupin, Piau, and Chabotet (2013).

The impacts of pavement-vehicle interaction on pavement damage and rolling resistance of vehicles are still being researched. Improvements in pavement deflection measurements such as rolling wheel deflectometers and advances in the modeling efforts of the ongoing studies will help facilitate the incorporation of structural responsiveness to vehicle fuel consumption calculations.

A sensitivity analysis is recommended to evaluate the critical variables and models impacting use-stage calculations. Sensitivity analysis can be conducted to evaluate the impact of speed assumption (variable vs. constant speed), rolling resistance/emission model (HDM-4 or EPA MOVES, or another source of emission factors capable of translating pavement rolling resistance to energy consumption and emissions) and models to predict structural related excess fuel consumption.

Radiative Forcing and Urban Heat Island

Changing the albedo of paved surfaces are among the several approaches proposed as potential mechanisms for addressing global warming (Van Dam et al. 2015). However, it should be noted that there is limited research demonstrating the practical effectiveness of those techniques, which includes changing the albedo of roofs and paved surfaces (NAP 2015). Although albedo changes can provide local cooling benefits (Campra et al. 2008; Li et al. 2013; NAP 2015), the efficiency of such strategies to reduce global warming is criticized since total changes in planetary albedo by implementing cool roof and pavement strategies may not compensate for a significant portion of the forcing produced by present or future human related radiative forcing caused by GHG (NAP 2015).

Research by Akbari, Menon, and Rosenfeld (2009) worked to define an average relationship between radiative forcing changes associated with surface albedo changes and to predict the impact on global climate patterns. Those estimates are viewed as oversimplified calculations founded on speculative assumptions, and are not based on rigorous adapted, unified, and detailed data sampling and simulations (Navigant 2010). Some of the potential sources of errors in the development of the fundamental relationships are related to the estimation of radiative forcing with an assumption of average cloud cover and ignoring to account for longer term effects of CO_2 (Navigant 2010).

On the other hand, there are ample studies addressing the impact of reflective surface (roofs and pavements) and urban green areas on local cooling patterns and resulting in changes in power demand and air quality. Generally, reductions in the CO_2 levels and air pollution, peak power demand, and energy costs use was shown to be achievable due to local cooling effects in summer times (Navigant 2010). A detailed summary of these studies is provided elsewhere (Navigant 2010; Van Dam et al. 2015).

Nevertheless, there remains a need for significant research and refinement in the models and calculations estimating local cooling patterns with respect to changes in surface albedo, specifically in terms of incorporating complicated interactions between different elements of the urban fabric, local conditions, interactions between rural and urban areas, and so on. A research project is currently underway, funded by the California Air Resources Board and the California Department of Transportation, to perform an LCA for implementation of high albedo pavement strategies in different cities and climate regions compared to normal practices (CARB 2013). The question of whether global changes in surface albedo can provide global cooling benefits remains uncertain.

A general framework for quantifying the effects of pavement albedo is provided in the guidelines section based on the existing studies. The method of calculating local and global cooling impacts resulting from surface albedo changes are not exact and subject to refinement. As climatic models continue to improve, the understanding of regional and global effects of changes in the surface albedo will be improved to determine whether increasing surface albedo of a region will have a net positive impact locally and globally.

Carbonation

Carbonation is the process where carbon dioxide is reabsorbed in concrete where it reacts with calcium from calcium hydroxide and calcium silicate hydrate to form calcium carbonate. The extent of the carbonation is dependent on the exposure to air which is limited to the surface in concrete, the humidity, and the permeability of the concrete. This process is defined as "passive" sequestration of CO_2 from the atmosphere by Carbon Leadership Forum (CLF) in the development of a concrete PCR (CLF 2013), and any form of "passive" sequestration occurring during the use stage or end-of-life stages is not included in the PCR of concrete.

Several studies suggest that carbonation can be a relevant parameter (Pommer and Pade 2006; Haselbach 2009). Most pavement LCAs that do consider carbonation, such as that described by Yu, Lu, and Xu (2013), follow a model developed by Pommer and Pade (2006).

It is recommended to perform a sensitivity analysis for carbonation using the available models. If carbonation proves to be a relevant parameter in terms of environmental significance, it should be included in the use stage.

Lighting

Electricity is used to illuminate roadways. The energy demand and upstream input-output flows should be considered when the pavement type itself affects energy demand. Lighting becomes a relevant use-stage component when the intended goal of a pavement LCA is a comparison between two pavements with different illumination demands. However, many state DOTs and other roadway agencies do not differentiate between surface types, partially because the long-term color and texture of pavement is unknown (Van Dam et al. 2015). Therefore, agency practices and specifications should be checked to calculate inventory parameters associated with lighting demand. Information on illumination demand according to roadway class descriptions is available from AASHTO (2008).

Leachate

The two potential sources of leaching from pavement materials are through runoff during the use stage and when pavement materials are deposited in the landfills. The two applications that may potentially pose a risk of leachate problems are pavement with recycled materials and use of seal coats (Santero et al. 2011). In general, most pavement materials do not leach into water, although they may affect the pH level and sometimes the degree of polycyclic aromatic hydrocarbon (PAH) found in some asphalt pavements (Santero et al. 2011). Most leachate from standard materials is from items deposited on the road by vehicles and the air, and not from the materials themselves.

Although there are some risks of leachate for a few pavement applications, there are some current issues in trying to quantify it in such a way to include in the LCA. If there are serious concerns about the leachate of a paving material or pavement application, site-specific measurements should be conducted to quantify the risk of leachability and include it in an inventory database.

4.3.4 Data Completion and Modeling

Emission factors available in the data sources discussed in this chapter can be used to populate the output flows consistent with the study requirements. Data completion and modeling are intended for calculating output flows when only process-activity data are collected or when collected data lack a complete list of emissions required for impact characterization.

Emission factors can be used for a single-unit process (e.g., kg of CO_2 released due to burning 1 gal of diesel in a generator or kg of SO_2 released due to burning 1 gal of fuel oil in an industrial boiler) or aggregate of processes (e.g., kg of particulate matter released per ton of asphalt mixture production). Primary data collection can be assisted using emission factors and by associating them with single-unit process data. An example is the calculation of the released emissions from an industrial boiler. In this example, the carbon monoxide emissions factor burning distillate oil in an industrial boiler is 0.6 kg CO per 10^3 L of oil burned (EPA 1995). The inventory list can be populated with individual emission factors for each unit process or using the life-cycle software equipped with libraries of unit processes.

Typical data collected through industry surveys and questionnaires are the amount of fuels and electricity consumed at different stages of production. It is also easy to collect production details and activity data (e.g., types of combustion, and equipment used, and hours of operation at the site of production). This information may be combined with emission factors for a specific process with known energy consumption and known type of internal or external combustion device (e.g., oil-fired or natural-gas-fired industrial boiler). An example of a combustion process with known inputs and calculated outputs is illustrated in figure 4-15.

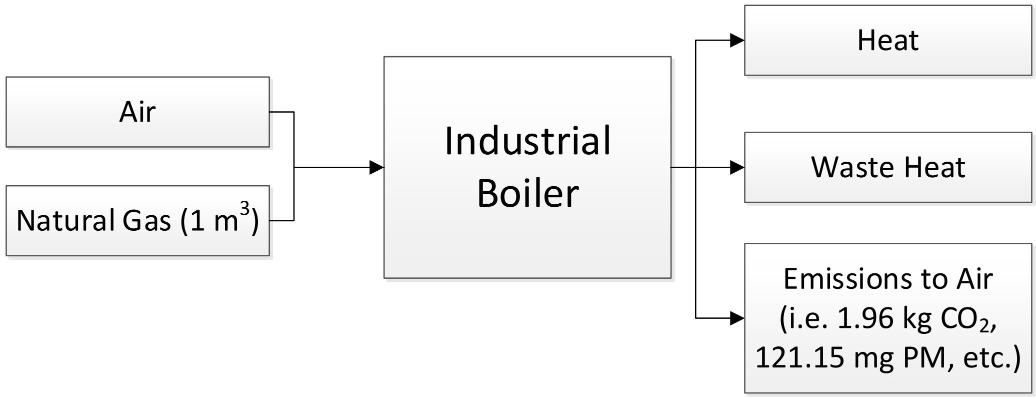


Figure 4-15. Use of combustion processes to estimate released emissions illustrating an example of industrial boiler unit process (Natural gas combusted in industrial boiler/U.S. in the Ecoinvent 2.1 database).

As an example, an HMA plant process is one of the most energy intensive unit processes included in an asphalt concrete pavement LCA, but it is actually an aggregate of multiple unit processes. Typical data collected from an HMA plant may contain diesel consumed during stockpiling and transfer of the materials in the plant (wheel loaders and trucks), fuel oil or natural gas combusted in the heating drum, and oil or electricity fired heaters for binder tanks and mixture silos. In addition to the energy consumption, input data include raw materials (aggregates, binder, and other ancillary materials), each of which are unit processes. However, these are not included in this example since this unit process only deals with the emissions released from plant processes.

The information in table 4-14 and 4-15 depicts how inventory results are populated using the primary process-activity data obtained from an average asphalt and ready-mix concrete plants. Energy sources and their combustion processes are given along with the emission factors used to calculate direct emissions (associated with the combustion of fuels). The information provided in the table also includes indirect energy and emissions associated with upstream production of energy sources combusted in various plant operations.

Table 4-14. (a) Example inventory data collected from a specific plant process for the production of 1 ton of asphalt mixture and (b) calculation of emissions using emission factors provided by unit process in Ecoinvent (data source: EarthShift 2013).

(a)

Known Inputs	Amount per ton of produced mixture	Combustion Source and Type	Source of Emission Factor
Diesel	3499 Btu (0.027277 gal)	General building machine used by wheel loaders (in plant operations)	Diesel, burned in building machine/GLO US-EI U (Ecoinvent)
Natural Gas	253 ft^3	Industrial boiler (drying aggregate)	Natural gas, combusted in industrial boiler NREL/US U (Ecoinvent)
Electricity	6853 Btu	Heating in binder and mixture storage tanks	Electricity, medium voltage, US IL (Egrid 2012 [EPA 2015])

(b)

Emissions	Direct* Diesel	Direct* Natural Gas	Direct* Electricity	Indirect** Diesel	Indirect** Natural Gas	Indirect** Electricity	Total
Primary Energy (MJ)	3.92	241.32	7.22	0.59	80.97	20.51	354.53
CO_2 (kg)	0.27	14.30	-	0.04	1.09	1.10	16.80
NO_x (g)	3.93	13.47	-	0.12	0.96	1.30	19.65
Methane (g)	0.01	20.60	-	0.16	84.34	1.42	106.54

* Inputs and Outputs per Ton of Produced Mixture Due to Combustion of Fuels (Direct)
** Inputs and Outputs per Ton of Produced Mixture Due to Upstream Production of Fuels and Electricity (Indirect)

Table 4-15. (a) Example inventory data collected from a specific plant process for the production of 1 cubic yard of Portland cement concrete and (b) calculation of emissions using emission factors provided by unit process in Ecoinvent (data source: EarthShift 2013).

(a)

Known Inputs	Amount per cubic yard of produced mixture	Combustion Source and Type	Source of Emission Factor
Diesel	50380.6 Btu (0.39222 gal)	Operating generator at plant	Diesel, burned in diesel-electric generating set/GL US-EI U (Ecoinvent)
Diesel	20769.8 Btu (0.16170 gal)	General building machine used by wheel loaders (in plant operations)	Diesel, burned in building machine/GLO US-EI U (Ecoinvent)

(b)

Calculated Outputs	Direct* Diesel (generator)	Direct* Diesel (loaders)	Indirect** Diesel (generator)	Indirect** Diesel (loaders)	Total
Primary Energy (MJ)	56.38	23.24	8.74	3.51	91.87
CO_2 (kg)	3.88	1.60	0.52	0.25	6.25
NO_x (g)	73.40	23.32	1.73	0.74	99.19
Methane (g)	0.01	0.08	2.2	0.96	3.29

* Inputs and Outputs per Ton of Produced Mixture Due to Combustion of Fuels (Direct)
** Inputs and Outputs per Ton of Produced Mixture Due to Upstream Production of Fuels and Electricity (Indirect)

The inclusion of indirect (or upstream) inputs and output flows associated with the production of fuel and electricity are recommended in the system boundary of plant production processes. Figure 4-16 illustrates the calculation of direct and indirect emissions for fuels and electricity. The same method applies to the calculation of indirect energy demand.

The activity data used in primary and secondary data are often expressed in terms of physical units of energy consumed (for example, m^3 of gas, gallons of fuel, tons of coal, etc.) during the data-collection phase. In order to convert these various physical units into energy consumed, the use of either lower heating values (LHV) or higher heating values (HHV) can be applied.[1] Table 4-16 summarizes some of the commonly used energy resources and their heating values. The use of LHV is recommended.

[1] Lower and higher heating values are defined by the U.S. Department of Energy (DOE 2011) as follows:

- The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered.
- The higher heating value (also known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products.

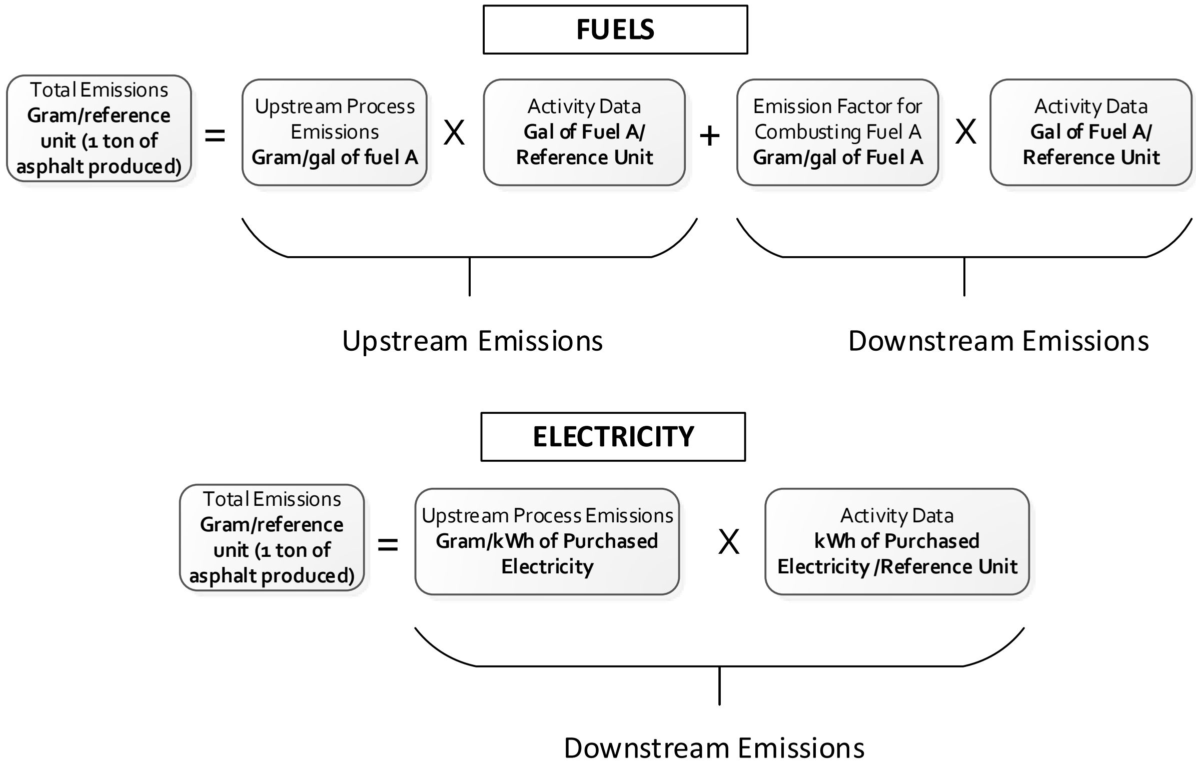


Figure 4-16. Calculation of upstream and downstream emissions for a typical unit process consuming fuel A and purchased electricity.

Table 4-16. Lower and higher heating values of combustible materials (ANL 2015).

Fuel	Lower Heating Value (LHV)	Higher Heating Value (HHV)
Crude Oil	129,670 Btu/gal	138,350 Btu/gal
Conventional Gasoline	116,090 Btu/gal	124,340 Btu/gal
U.S. Conventional Diesel	128,450 Btu/gal	137,380 Btu/gal
Residual Oil	140,353 Btu/gal	150,110 Btu/gal
Liquefied Petroleum Gas (LPG)	84,950 Btu/gal	91,410 Btu/gal
Propane	84,250 Btu/gal	91,420 Btu/gal
Natural Gas	983 Btu/ft^3	1089 Btu/ft^3
Pure Methane	962 Btu/ft^3	1068 Btu/ft^3
Gaseous Hydrogen	290 Btu/ft^3	343 Btu/ft^3
Coal for Electricity Generation	19,474,169 Btu/ton	20,673,610 Btu/ton
Bituminous Coal	22,639,320 Btu/ton	23,633,493 Btu/ton
Petroleum Coke	26,949,429 Btu/ton	28,595,925 Btu/ton

4.3.5 Data Validation

After following the steps provided in the guidance section, benchmark comparison is commonly conducted as part of data validation. An example of such a benchmark comparison is provided in figure 4-17 for aggregate production.

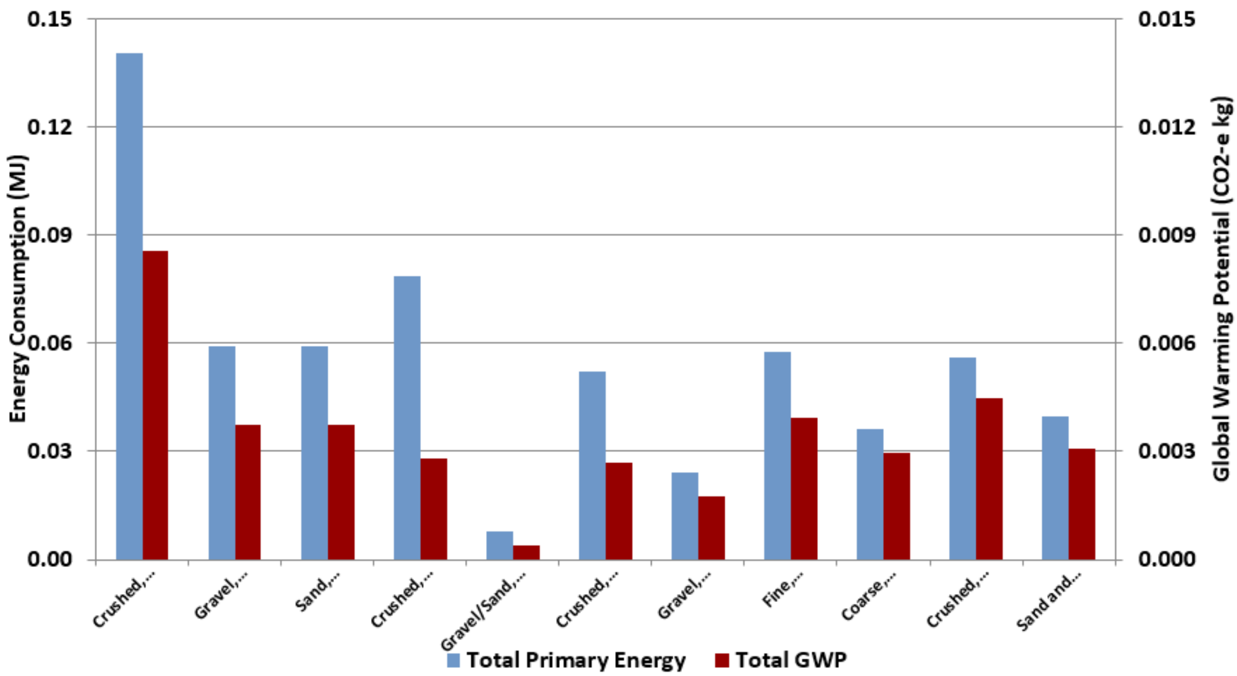


Figure 4-17. Primary energy and global-warming potential from aggregate production per kg, at quarry (after Wang et al. 2012).

4.3.6 Data Aggregation

Data aggregation targets combining the data collected from multiple unit processes representing different life-cycle stages. For example, cement production requires acquisition of raw materials (e.g., quarrying processes for limestone, gypsum, and other minerals), fly ash acquisition, ancillary materials, energy inputs and their production processes (e.g., electricity, production, quarrying coal, gasoline, etc.), and plant production processes (e.g., combustion of gasoline, coal and energy sources). Inventory inputs and outputs collected in steps 3 and 4 (shown in figure 4-3) for each one of these materials and processes are aggregated in this step following the flow diagrams and quantities required to produce unit mass or volume of aggregated process. An aggregated inventory inputs and outputs for portland cement at the end of materials-production, data-collection phase is shown in table 4-17.

Table 4-17. Typical materials-production inventory results collected and calculated at the materials and production stage of portland cement (NREL 2015).

Input/ Output	Flow	Category	Type	Unit	Amount
Inputs	Bituminous coal, combusted in industrial boiler	None	Product Flow	kg	1.07×10-1
	Electricity, at grid, U.S. 2000	None	Product Flow	kWh	1.44×10-1
	Gasoline combusted in equipment	None	Product Flow	L	1.33×10-4
	Natural gas, combusted in industrial boiler	None	Product Flow	m3	5.57×10-3
	Limestone	Resource/ground	Elementary Flow	kg	1.37×100
	Gypsum	Resource/ground	Elementary Flow	kg	6.15×10-2
	Fly ash	None	Product Flow	kg	1.35×10-2
Outputs	Portland cement, at plant	None	Product Flow	kg	1.00
	Carbon dioxide	Emissions to air	Elementary Flow	kg	3.74×10-1
	Carbon dioxide, fossil	Emissions to air	Elementary Flow	kg	5.53×10-1
	Oils	Emissions to water	Elementary Flow	kg	7.52×10-6
	Sulfate	Emissions to water	Elementary Flow	kg	6.16×10-4

*Flows are compressed for brevity of presentation.

4.3.7 Translate Data to Unit Processes and Functional Unit

Aggregated inventory results should be described in terms of the functional unit chosen for the LCA, and calculation procedures may vary with different life-cycle stages. As an example, consider an LCA study performed for a project with a functional unit of 1 lane-mile and with a 3-inch HMA overlay. In the unit process level, 80 kg of asphalt binder are needed to produce 1 ton of HMA for a generic mixture or a specific mixture volumetrics obtained for the project. For 1 lane-mile of a 3-inch HMA overlay, assume that 1148 tons HMA are needed. After relating the data to the functional unit, (80 kg/per ton of HMA x 1148 ton HMA), 91.84 tons of asphalt binder are needed for 1 lane-mile of a 3-inch HMA overlay. Inventory input output flows can be expressed in terms of reference flow (1148 tons for HMA and 91.84 tons for asphalt binder) or per unit mass or volume (i.e., 1 ton of HMA produced). If the inventory database is developed per unit mass or volume of production, data can be translated to the functional unit during aggregation of unit processes. For practical purposes, inventory database per unit mass or volume of production is preferred to be consistent with commercial and literature data sources expressed in term of unit mass or volume production.

4.3.8 Allocation for Flows and Releases

Manufacturing Processes with Co-products

The preferred way to deal with assigning impacts to multi-outputs is to reflect the physical properties of the outgoing flows, such as mass or energy content. This means that the physical basis for allocation can be different for different situations and for different materials. The economic value of co-products may also be used for allocation; however, Bernard, Blomberg, and Southern (2012) suggest that allocation based on physicochemical properties (e.g., mass or energy content) is preferred to economic allocation. On the other hand, Ayer et al. (2007) and Guinee et al. (2002), among others, have stated a preference for economic allocation above other approaches, largely because economic value is typically the primary driver of business.

Allocation requires a partitioning of the coproducing processes without considering the interactions between sub processes; thus, an objective justification is warranted between the chosen allocation parameter, such as mass or economic value, and the share of environmental loads (Weidema 2001). Manufacturing process can be analyzed at an aggregated level where total energy consumption and emissions are distributed to co-products based on the selected allocation option. However, aggregated allocation option cannot capture process dependent characteristics of inputs and outputs in some complex systems. Alternatively, process-level method can be used for such complex production systems as recommended by ISO 14044 and ISO 14049 when possible. Process-level method starts with mass and energy flow in the entire process and tracks inputs and outputs by the individual subprocesses of the production. At each individual subprocess, mass, energy or economic allocation options can be used. This makes co-product allocation sometimes contentious. Proper LCA practice in this case requires justification for allocation, transparency in reporting, showing the impact of allocation choices on the results, and performing sensitivity analyses to assess the significance of the allocation choice on the overall LCA conclusions.

An example allocation for asphalt-binder production is provided in the callout box on the following page, while an example of an economic allocation for a multi-output process is shown in figure 4-18. Refinery operations are one of the complex production systems with many individual processes with distinctive inputs and outputs and each one of the refinery co-products go through different process in the refinery. For such systems, best practice is to perform process-level allocation approach (Wang, Lee, and Molburg 2004). This study found that aggregate refinery level allocations could overpredict energy use for some refinery products but underpredict for others. However, access to such detailed operational information from refineries is limited for proprietary reasons. Therefore, second best option, when process-level details are not available, is to perform refinery level aggregated allocation using economic based method as also shown in the example demonstration of ISO 14049.

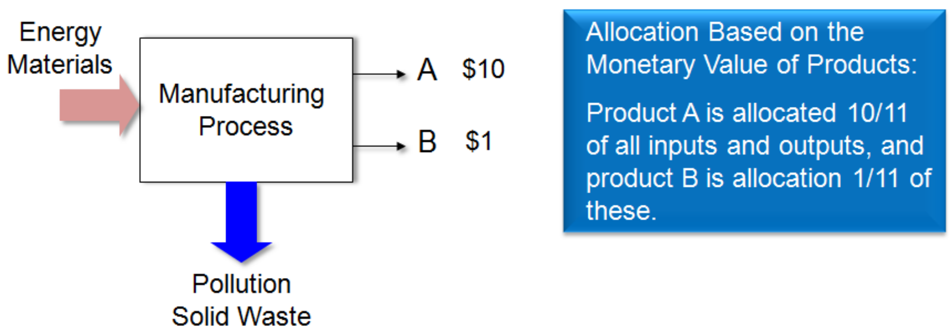


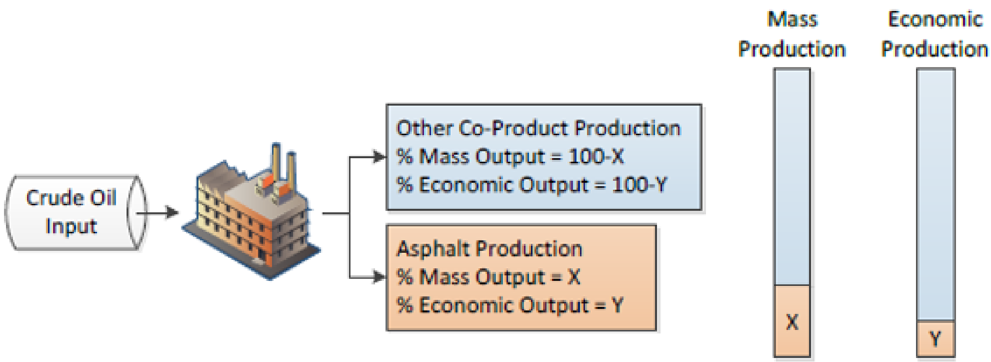
Figure 4-18. Example of economic allocation for a multi-output process.

In summary, refinery operations are complex, but allocation is needed. Recommended approach is to perform process-level approach where individual processes are tracked and allocated to the refinery products processed. When specific process data is not available, aggregated refinery level allocation could be the second option with economic-based method. Refinery production statistics obtained from EIA and other public sources can be used to perform refinery level allocation. Economic-based allocation is sensitive to mass share and price of refinery products. Therefore, most relevant and specific information with regards to mass share and price index in a refinery should be obtained. If source of asphalt binder is known, production statistics data from the refinery should be used to perform allocation. Regional averages gathered in each Petroleum Administration Defense Districts (PADD) can also be used when specific refinery sources are not known (Yang 2014 and Yang, Ozer, and Al-Qadi 2016).

Example of Allocations for Asphalt Binder Production (Based on ISO 14049)

Asphalt binder is a good example of the need for the application of proper allocation methods. Asphalt binder, along with a number of other products, are all produced from the same input crude oil. The first step in the process is to check if allocation can be based on physical parameters, e.g., mass, volume, energy, etc. For the refinery operations, the physical relationship between asphalt and other co-products can be easily established for petroleum extraction and transportation. Thus, using allocation based on physical parameters can be reasonable for these two phases. However, for the refinery stage, applying a physical allocation is not appropriate because there are no clear underlying physical relationships between asphalt binder and the other co-products that result from crude oil refining. In other words, increasing mass yield of one of the refinery product may not result in proportional increase in the energy use at the refinery level. According to ISO 14049, physical allocation cannot be used if, for example, the physical ratio between asphalt and other co-products can be varied in the refinery with incurring significant, complex changes in the refining processes themselves (ISO 2006c). This implies that physical allocation is not possible, and economic allocation must then be used in this case. However, when process-level method is performed following production paths of each refinery product, physical or economic allocation options can be used when applicable (Wang, Lee, and Molburg 2004).

In this example by Yang (2014), yield is used as physical parameter, and it is assumed that there are no co-products. Other physical parameters, if suitable, can also be used to replace yield.



The allocation factor (F) is calculated to record inputs and outputs per reference flow for asphalt binder (i.e. primary energy per ton of binder, GHG per ton of asphalt binder). For petroleum extraction and transportation is "X/X = 1.0" illustrating mass residue yield. The allocation factor (F) for refinery operations can be calculated by taking the ratio between the economic production coefficient (Y) and mass residue yield (X):

$$Y = \frac{Yield(a) * Price(a)}{\sum_{i=1}^{n} Yield(i) * Price(i)} \quad \text{and } F = \frac{Y}{X}$$

For example, for PADD Region 2 (midwest), the economic production coefficient is 0.0344 while the mass residue yield is 0.0818. This means that only 3.44 percent of the total economic output of the refinery is asphalt, while 8.18 percent of the total mass output of the refinery is asphalt. The allocation factor calculated with respect to market value is 3.44/8.18= 0.42, which implies that the amount of energy allocated to asphalt should be 0.42 that of the average petroleum product.

Splitting up the refinery into the different processes can alleviate some of the allocation difficulties as some processes can be directly assigned to asphalt binder (storage, pumping) and others can be assigned by mass as well (like vacuum distillation).

Reuse of Components and Recycling of Materials after Initial Use

When using a material from another product, pavement, or system, several approaches for allocation have been and are being tried to ensure that the "benefits" of using secondary materials or fuel resources are properly reflected in an LCA. Most EPD approaches use a strict and conservative approach: all processes and transportation needed to reuse or recycle the material are assigned to the product utilizing the recycled content, but the production of the original product is assigned to the first product's life cycle. The same is true of reused or recycled materials that are used in pavement projects, such as the secondary content in steel, recycled aggregate from building waste, rubberized-asphalt binder containing recycled tires, recovered binder from asphalt shingles, and SCMs derived from other industrial processes. Furthermore, materials that become available for reuse or recycling at the end of the pavement life cycle, such as RAP, RCA, and reinforcing steel, are also allocated in this manner.

If an economic approach is used to define a resource as a waste or a co-product, the following factors should be considered:

- Where a waste flow has positive economic value, it is considered a co-product and should be treated as such.
- Where a waste flow material has a negative value; but becomes an economically valuable product through processing, the impact of processing and handling is allocated based on the difference between the cost (assigned to the producing life cycle where the waste occurred) and the positive value (assigned to the receiving life cycle where the co-product is used). An example of this is concrete waste that requires an acceptance fee at a crushing facility where it is processed (crushed and sized), and then sold back to the market at a price.
- Where the waste remains at a cost regardless of processing, all environmental burdens of the processes are assigned to the producing life cycle; in this case, it essentially stays a waste and never becomes a co-product. The life cycle that uses materials like this are essentially part of the waste treatment process and receive the material "for free."

Other approaches assign a "value" to the recycled materials and include credits for preventing the need for new primary materials for the new application. This is referred to as substitution, and must be considered cautiously and aligned with the approach for the receiving product system.

One variation of assigning credits for recycling is the modeling of multiple life cycles to reflect repeated recycling benefits. This approach is typically used to assign future recycling credits to the current product. There are examples reported where an infinite number of life cycles are modeled to show the benefits of recycling, which can extend time periods that are irrelevant on a human scale. This is not considered a good LCA practice in pavements, particularly given that modeling a pavement over a period in the range of 50 to 75 years is significantly challenging enough.

Waste Treatment Processes

The preferred way to deal with assigning impacts to multi-input processes is to reflect the physical properties of the incoming flows. If a relationship can be established that is more suitable than mass, it should be used. An example is the relation between the chemical composition of a waste that is available for landfill and the associated emissions to air and water from the landfill. However, this is not very relevant for most pavement LCA materials since most of them are inert. Another example is the relation between the chemical composition of a waste that is available for incineration and the associated emissions to air and energy recovery as heat or electricity. Both situations occur in pavement LCA but are not fully relevant to the outcome of most pavement LCA materials since most of them are inert or have little or no economic value as a combustion energy source.

4.3.9 Decision Rules and Refining System Boundaries

The commonly used decision criterion for including or excluding material and energy inputs and emission, waste, and product outputs is mass based. Nevertheless, that does not mean this should always be the case. Some pavement-related examples are the exclusion of warm-mix additives (less than approximately 0.1 percent of the mass of total asphalt mixture) and other additives (polyphosphoric acid [PPA], anti-stripping agents) in asphalt-binder modification, and some of the admixtures used in cement manufacturing (water reducers, shrinkage reducers, accelerators, retarders). Most remain under a 1 percent by mass-based cutoff criterion for asphalt mixture production and cement manufacturing processes, respectively. However, an analysis of environmental relevance for justification of their initial exclusion should be documented, and this is usually lacking in current pavement LCA. As a general

Allocation Scenarios for Supplementary Cementitious Materials (SCMs)

There is debate on how to allocate environmental impacts for high value SCMs, such as fly ash and slag cement. In the past these materials were considered wastes from industrial processes (coal-powered electricity generating fly ash, and steel production generating blast furnace slag). The current practice in the U.S is to consider fly ash a waste material diverted from a landfill for beneficial use, meaning that none of the environmental impact associated with electricity generation is typically assigned to the fly ash. As long as the cost of transport and processing the fly ash is the only source of economic value, a waste classification is appropriate. However, once the fly ash has value beyond this, it should no longer be considered waste, but instead a co-product. Already in some markets fly ashes are in high demand and economically valuable, meaning they are no longer waste flows. In these cases, it is appropriate to allocate some of the environmental burden associated with coal-fired power plants to fly ash. The most common means to accomplish this is through economic worth of the co-products. LCAs in some regions (e.g., Europe) show that the economic worth of fly ash compared to electricity generation is small and hence the assigned environmental impacts are also small.

The same practices can be applied to slag cement (also known as ground granulated blast furnace slag) derived from blast furnace slag from steel production. It is noted that different allocation methods can lead to differences in assigned environmental impacts. There are also other motivations for industries to seek classification as waste or co-product. For example, in Europe, fly ash producers often do not want classification as "waste" because that requires a much more difficult regulatory environment for handling, storing, and transporting the material. Chen et al. (2010) considered different allocation methods for slag cement and fly ash used in Europe, arguing that demand for these products outpaced production and thus their designation as a waste may not be appropriate. Allocation based on economic value as compared to allocation by mass leads to significantly lower environmental flows attributable to both SCMs, and seems to better reflect the purpose of the industries that produce the SCMs, i.e., the production of steel or electricity. Recently published slag cement EPD for US and Canada markets considers blast furnace slag as a waste material and categorized it as "recovered waste material" (ASTM 2015).

rule, mass-based cutoff is not recommended for highly processed chemicals or additives that may be used in pavement construction unless it is justified by the environmental significance rule.

It is recommended to use the environmental significance as an additional criterion that has to be met. A good example is the inclusion of all hazardous and toxic materials. The cement and concrete PCR from the Carbon Leadership Forum specifically mandates that all of the inputs identified as hazardous and toxic should be included in the inventory (CLF 2013).

A consistent approach should be followed for the inclusion/exclusion of infrastructure and capital goods to a unit process. Capital goods are installations and equipment that are used but not consumed in a process, and typically large volumes of products are processed using the same capital goods. An example is a refinery or cement plant. Infrastructure processes and equipment relates to the grid for electricity, or to the highway for truck and personal transportation, the airport for air traffic, and so on. Infrastructure and capital goods are usually not included in current pavement LCA studies, but some databases offer the option to either include or exclude infrastructure data. An example is the Ecoinvent database that allows for sensitivity analysis to evaluate the relevance of infrastructure processes. Therefore, modification of individual unit processes may be required if the infrastructure is excluded.

In some instances, infrastructure has some relevance. For example, European asphalt-binder inventory developed by Eurobitume (2011) evaluates the options to include or exclude infrastructure. The study concluded that infrastructure can have some relevance especially in countries with low productivity per borehole during the stage of crude extraction. Hence, data without and with infrastructure were presented. The comparison shows that infrastructure has to be considered to obtain the emissions and resource uses in the life cycle. Thus, it was recommended to include infrastructure in most cases (Eurobitume 2011).

4.3.10 Data-Quality Assessment

A brief discussion on the major data-quality requirements and indicators is provided in this section with examples from the literature. Following the discussions on individual data-quality requirements, a detailed discussion on how the step-by-step procedures (introduced in the guidance section) to assess data quality will be presented.

Time-Related Coverage

Time-related coverage is defined as "age of data and the minimum length of time over which data should be collected" in ISO 14044 (ISO 2006b). According to ISO 14049, site specific data are primary data, while data from published sources are secondary data (ISO 2006c). The data include product specific information (in the case of pavement LCA product is pavement) and inventory database. Pavement specific information (structure, materials and resources matrix with supplier and contractor data, traffic volume, etc.) should represent the time period of the pavement construction and use. On the other hand, time-related coverage for LCI databases refers to the inventory input and output collected for each unit process. Based on ISO 14049, key suggestions regarding time-related coverage are listed below (ISO 2006c):

- Primary data within the last year.
- Secondary data (published sources) within the last 5 years that are properly documented, calculated, or estimated.
- Justification to be provided if the data sources break the above two rules.

- Qualified primary data are considered better sources than qualified secondary data.
- Primary data collected for at least a 1-year period since the data can provide seasonal effects, natural process variation, and accidental events.
- Consistency checks for the most recent primary data with data from previous years for any potential anomalies or reporting errors.

There are numerous examples illustrating the importance of temporal coverage of product specific and inventory data. The changes in the data with time can be due to a number of factors, such as technology changes, pavement construction activities, changes in suppliers, changes in the rehabilitation schedules, changes in traffic volume and composition, and changes in rules and regulations. A specific example is the difference in winter and summer production for processes that require heating or cooling and take place in the open air (such as an asphalt plant or a precast concrete plant that requires heating during winter production). Looking at annual data also allows for the inclusion of gross efficiencies, e.g., from stops and starts.

Figure 4-19 shows an example for particulate-matter emission for a diesel paver using EPA's NONROAD (EPA 2008b) program within a time period from 1990 to 2014. The reduction in the PM emissions is significant as the EPA regulations changed over the last decade.

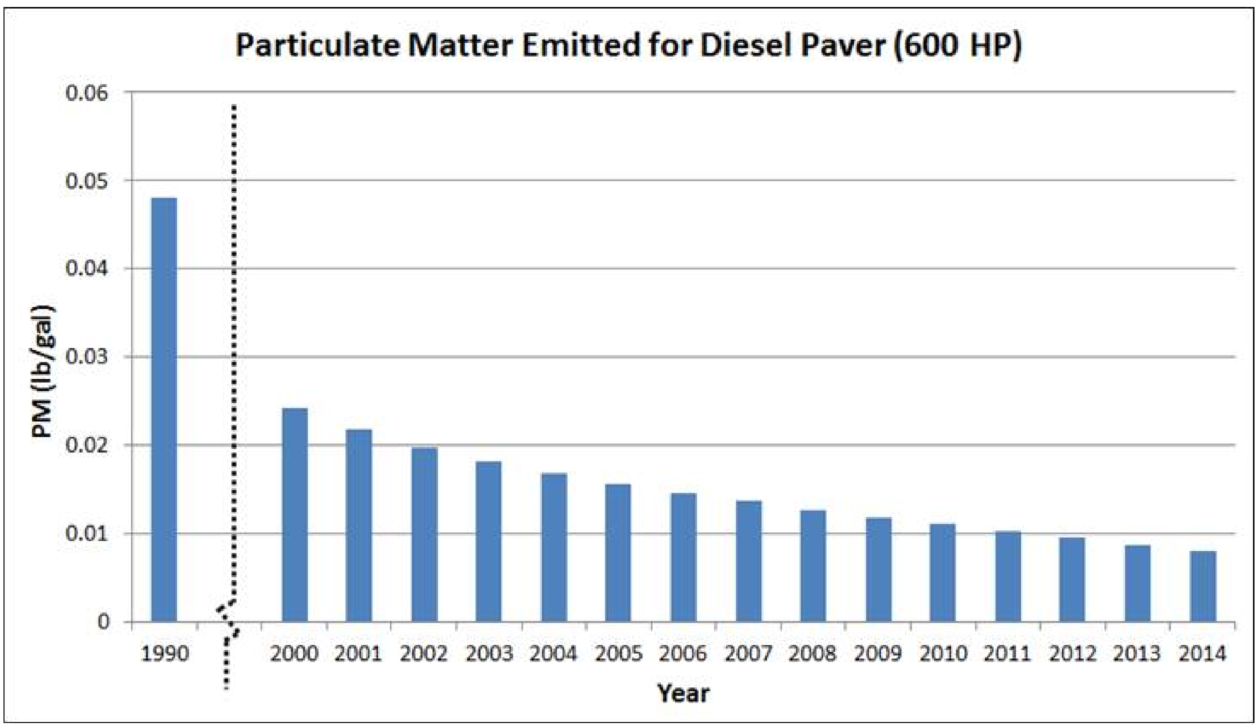


Figure 4-19. Variation of particulate-matter emissions from a diesel paver between 1990-2014 (data source: EPA 2008b).

Geographical Coverage

According to ISO 14044 (ISO 2006b), geographical coverage refers to the area from which data for unit processes should be collected to satisfy the goal of the study. Geographical coverage should include site or regional specific facility or practices within the system boundary of unit processes. Resolution of spatial coverage depends on overall data availability and the specific goals of the study. Facility or site primary data can be available for production of concrete, asphalt mixture, pavement construction, traffic volume and mix, whereas regional data (statewide or other representative geographic subregions) can be available for electricity and fuels. Spatial coverage may not be limited to only regional facilities since the supply chain may extend beyond a specific region where the raw materials are produced.

Regional or site specific pavement data and inventory database are relevant for the overall quality and representativeness of the LCA performed. However, developing a regional database is a challenging task as data are not always available; therefore, a data-collection strategy consistent with the goals of the study has to be developed to compile a suitable regional database, particularly for primary processes that may significantly contribute to the LCA outcome. When site or regional primary data cannot be found, best-matched data can be used for some unit processes.

It is important to recognize the geographical information for a unit process and use the best-matched data for it. An example illustrating regional as well as temporal variations is illustrated in figure 4-20 for electricity production in the U.S. Electricity production is relatively well documented and archived for different regions in the U.S., thereby allowing higher resolution in the regional and temporal representation (EPA 2015). Therefore, representativeness of electricity production inventory data can be easily improved by using appropriate data from the EPA's eGRID database. Another example (see figure 4-21) shows the energy consumption and GWP for asphalt-binder production of different U.S. regions (Yang 2014). The five regions include East Coast (PADD1), Midwest (PADD2), Gulf Coast (PADD3), Rocky Mountains (PADD4), and West Coast (PADD5). According to figure 4-21, the total results for the various PADD regions are different, as well as the combination of percent contributions of each step. For example, the difference between PADD1 (the highest) and PADD4 (the lowest) is 24 percent in energy consumption and 41 percent in GWP. PADD1 has the highest energy consumption and GWP because of flaring in the overseas oil fields that supply it with crude and foreign crude transportation. In this case, if the U.S. average values are used for PADD1 and PADD4, the environmental burden of asphalt-binder production is underestimated or overestimated, respectively.

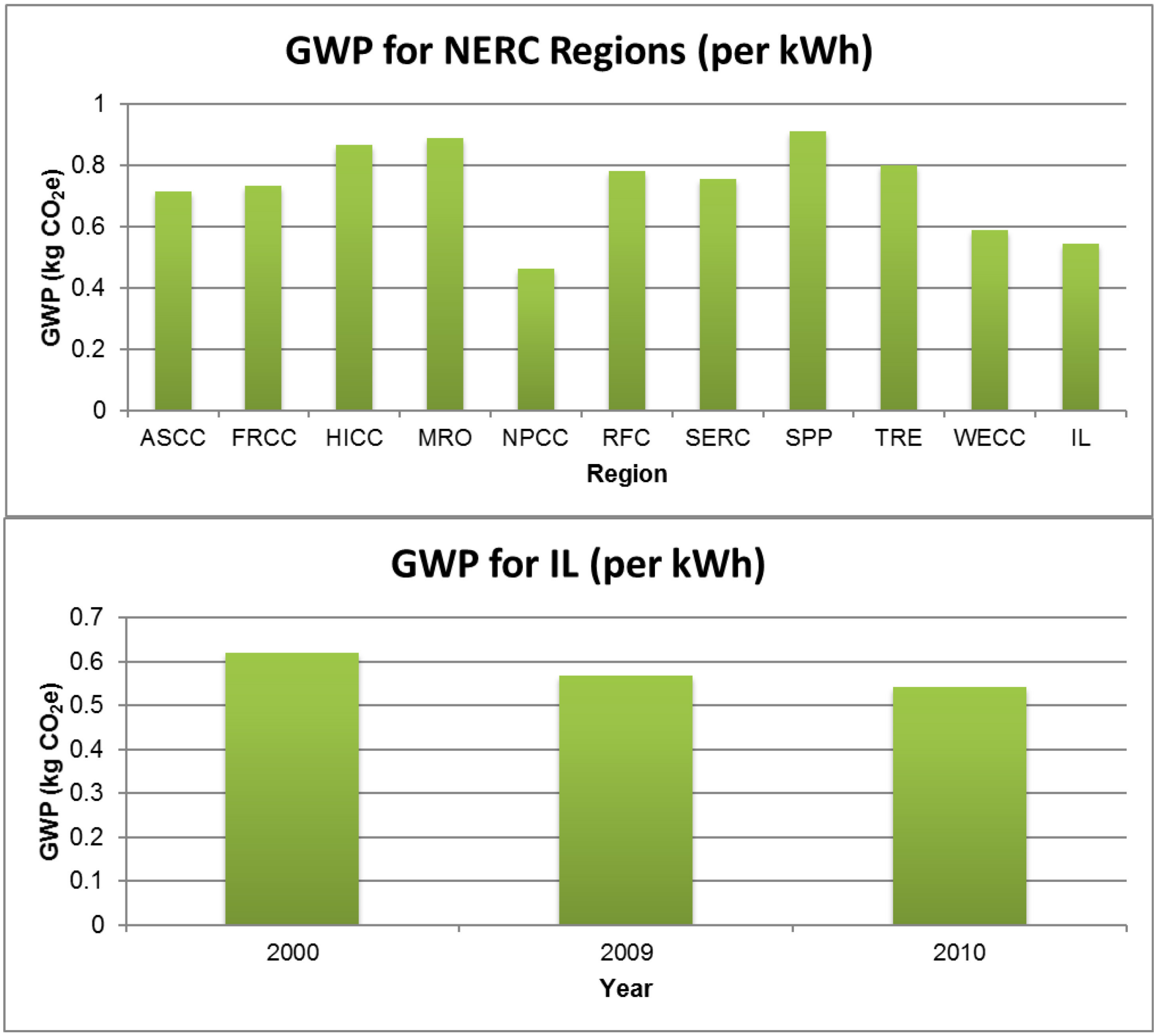


Figure 4-20. Regional and temporal variations in power production in different regions of the U.S. (data source: EPA 2015).

ASCC: Alaska Systems Coordinating Council, FRCC: Florida Reliability Organization, HICC: Hawaiian Islands Coordinating Council, Oahu, MRO: Midwest Reliability Organization, NPCC: Northeast Power Coordinating Council, RFC: Reliability First Cooperation, SERC: SERC Reliability Corporation, SPP: Southwest Power Pool, TRE: Texas Regional Entity, WECC: Western Electricity Coordinating Council, IL: Illinois

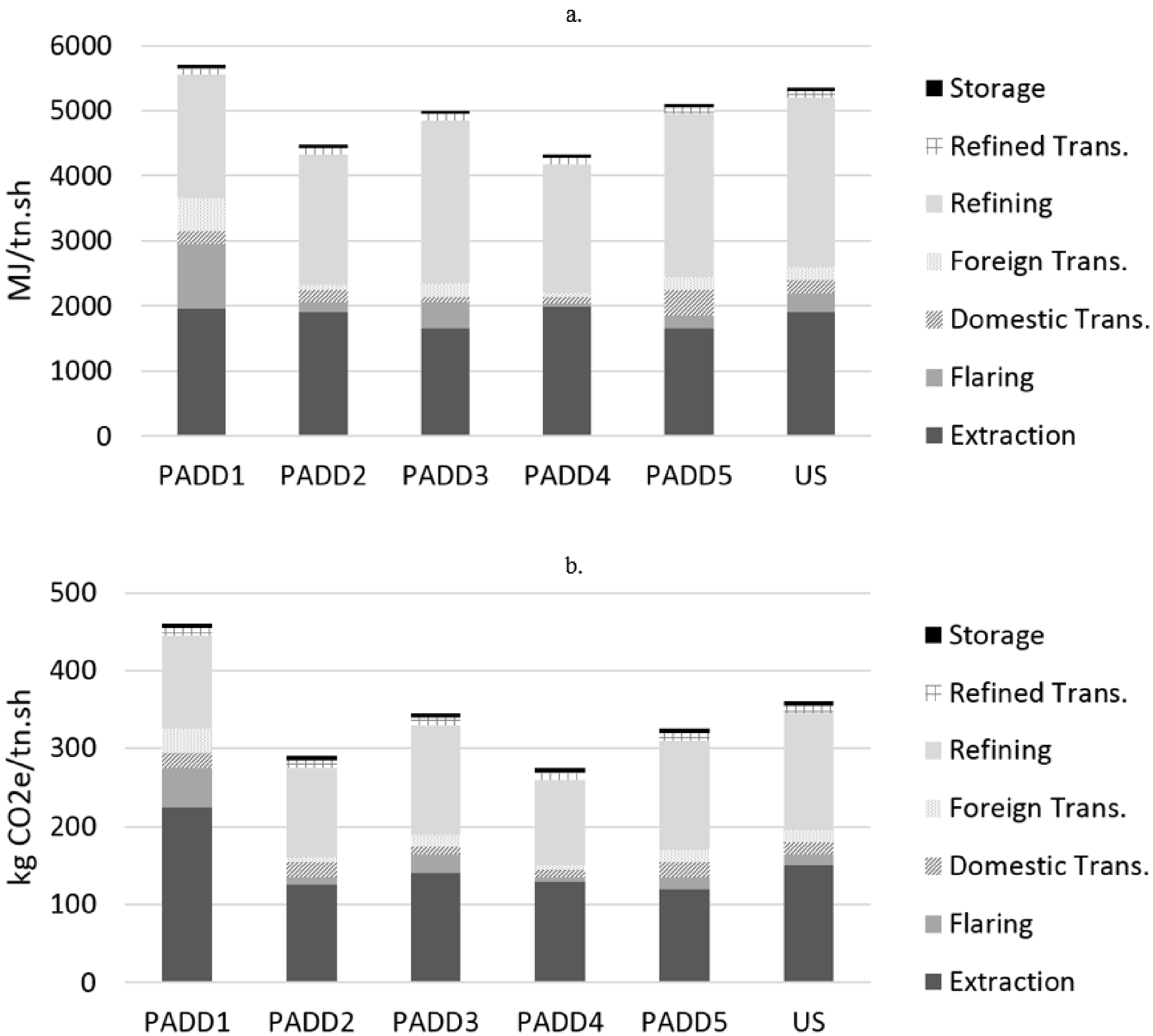


Figure 4-21. Life-cycle results for asphalt-binder production with respect to different regions in the U.S. (Yang 2014).

Technology Coverage

According to ISO 14044 (ISO 2006b), technology coverage refers to specific technology or technology mix used in the life cycle of the product. In the case of pavement LCA, technology covers the material-production and construction processes reflecting current state of the practice for the intended application. Based on ISO 14049 (ISO 2006c), key recommendations regarding technology coverage include:

- Define the inherent characteristics of the production, process, and environmental control technologies. The internal documentation of agencies (specifications, guidelines, previous contract documents) can provide a useful inspection of technology coverage representative of the intended application.
- Technological development is preferred to be considered when the total life cycle covers a time period where such a development can be expected. This may require scenario-based

analysis as the information may not be readily available. When technology is kept the same with the currently available information, the result may underestimate the impact from the past whereas it may overestimate the impact in future.

The manufacturing of cement in the U.S. can be considered as one example of the importance of capturing technology changes. There are four cement plant process types, including wet, long dry, dry with preheater, and dry with preheater and precalciner. The wet process technology is the most energy intensive in the manufacture of clinker for cement, whereas the dry process with preheater and precalciner is the most energy efficient. The wet process is no longer widely used, which illustrates the importance that the LCI data collected for cement be representative of the most current technology. A similar example exists for the production of asphalt mixtures, which can be produced in either batch or drum plants, the latter of which have improved significantly over the years (e.g., capability to handle mixes with high recycled content and WMA, more efficient exhaust fan technologies, use of binder storage tanks, and so on).

Precision

According to ISO 14044 (ISO 2006b), precision is a measure of the variability of the data values for each data expressed. Means and standard deviations (or variances) of reported values are preferred to be calculated and reported for each unit process within the system boundary. The availability of standard deviations also helps to identify the potential for conducting sensitivity analysis or to quantitatively assess the uncertainty of the pavement LCA results.

The Ecoinvent guideline (Weidema and Hischier 2010) provides quantities for measured uncertainty based on expert estimates and distribution assumption. A pedigree matrix (Weidema and Wesnæs 1996) is used to estimate the standard deviation for each input and output that are related to each unit process. An overall pedigree score can be calculated based on such characteristics as reliability, completeness, temporal correlation, geographical correlation and further technological correlation; from there, the pedigree score can be translated into variances reflecting the precision of the data.

Completeness

Completeness is defined as percentage of flow that is measured or estimated. A percentage target with respect to a cutoff rule is generally agreed for each type of unit process before data collection begins. The cutoff rule can be based on mass, cost, or environmental impact. For example, all materials that contribute to a unit process (e.g., 1-ton-asphalt mixture production, 1 cubic yard of concrete) at a level of more than 1 percent can be included. For materials that contribute less than 1 percent, the material can be included if the contribution to environmental impact is more than 1 percent. Completeness can be achieved within a study's defined cutoff criteria of mass, cost, and environmental relevance. A sensitivity analyses is recommended to help determine the necessity of including certain materials.

Consistency

Consistency is defined as a qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis. It is necessary to ensure that the assumptions, methodologies, and data used in different components of the study are compliant with the goal and scope of the study. It is preferred to provide a short report or a summary table presenting the consistency checks for all important assumptions (e.g., system boundary), methodologies (e.g., cutoff rules), and data requirements (e.g., temporal, geography, technology etc.). When data are collected from multiple sources in different countries and continents, it is crucial to document what data are being requested, how they are measured, how the data are reported, and how they are used.

Reproducibility

If a qualitative assessment of the extent of information regarding the methodology and data values is available, this allows an independent practitioner to reproduce the results reported in the study. To achieve reproducibility, the important assumptions, methodologies, and data sources are necessary to be transparent. A detailed discussion and guidance on the step-by-step procedures introduced in the guidance section is presented as follows with examples.

1. **Development of Quality Scoring Criteria.** The first step in the evaluation of the data quality is the development of scoring criteria. The scoring criteria may change depending on the LCA application, but it should contain all or most of the data-quality indicators. An example scoring criteria (considering representativeness of the unit processes in terms of technology, time, geography, completeness, and reliability) is presented in table 4-18. Different variations of scoring criteria can be adapted for a specific LCA study.

Table 4-18. Scoring criteria: representativeness to the process in terms of technology, time, geography, completeness and reliability (GHGP 2011).

Score	Technology	Time	Geography	Completeness	Reliability
Very good (1)	Data generated using the same technology	Data with less than 3 years of difference	Data from the same area	Data from all relevant process sites over an adequate time period to even out normal fluctuations	Verified data based on measurements
Good (2)	Data generated using a similar technology	Data with less than 6 years of difference	Data from a similar area	Data from more than 50 percent of sites for an adequate time period to even out normal fluctuations	Verified data partly based on assumptions or nonverified data based on measurements
Fair (3)	Data generated using a different technology	Data with less than 10 years of difference	Data from a different area	Data from less than 50 percent of sites for an adequate time period to even out normal fluctuations or from more than 50 percent of sites but for shorter time period	Nonverified data partly based on assumptions or a qualified estimate (e.g., by sector expert)
Poor (4)	Data where technology is unknown	Data with more than 10 years of difference or the age of the data are unknown	Data from an area that is unknown	Data from less than 50 percent of sites for shorter time period or representativeness is unknown	Nonqualified estimate

Another commonly used approach for data-quality assessment is the use of a pedigree matrix, originally developed by Weidema and Wesnæs (1996). Ecoinvent (2016) uses this approach to estimate the standard deviation based on six of the data-quality indicators including reliability, completeness, temporal correlation, geographical correlation, further technological correlation, and sample size. The score for each criterion ranges from 1 (best) to 5 (worst), and a factor (U) is assigned with a lognormal distribution and a standard deviation increasing with deteriorating data quality. For example, a data-quality score for data less than 3 years old is 1 and the assigned U factor is 1.0, while a data-quality score for data whose age is unknown or more than 15 years is 5 and the assigned U factor is 1.50, indicating 50 percent standard deviation.

2. **Assessment of Data Representativeness for Each Unit Process.** The second step is the evaluation of representativeness of each unit process. Scoring criteria can again be used to evaluate the representativeness of the data-collection strategy. If literature sources are used, the external source should be subjected to the same assessment. The inventory report should include a representativeness evaluation of the sources used in developing the unit process. Table 4-19 provides an example of the sources evaluated for binder production. Depending on the scoring criteria agreed on, one can evaluate the representativeness of one of these sources that can be used as binder-inventory data.

Table 4-19. Assessment of individual-data source representativeness.

Name (latest version)	Year	Region	System Boundary	Reproducibility & Transparency	Technology Coverage	Completeness	Precision
Ecoinvent 3.1	Various	EU and US	WTB[3]	provided	Provided	provided	provided[1,2]
Stripple 2001	Before 1995	Sweden	WTB	provided	Provided	Not provided	provided[1]
Eurobitume 2011	2011	Europe	WTB	provided	Provided	provided	provided[1,2]
Häkkinen and Mäkelä 1996	1992	Finland	WTR	Not provided	Not provided	Not provided	Not provided
Athena 2001	1970 to 1990s	US	WTB	provided	Provided	provided	provided[1]

1 Precision is due to using regional or state specific or actual plant production data
2 Precision is due to addressing uncertainty with data-quality indicators or rating
3 WTB (well to blending) includes crude production, crude transportation, refining, transportation to blending terminal, and blending and storage, well to refinery (WTR) includes crude production, crude transportation, and refining.

3. **Scoring for Individual Unit Processes.** The third step is an assignment of a data-quality score for the unit processes. Each data point used to develop the inventory results for unit processes can be evaluated with the information available. This is usually possible for primary data but more difficult for secondary data, especially if the author has not performed this type of assessment or did not report on it. Each unit process or major unit processes receives a data-quality score based on the scoring criteria and representativeness assessment.

4. **Overall Scoring with Data Aggregation.** Finally, unit processes are aggregated to develop an overall score for major products and processes included in the pavement LCA. Table 4-20 illustrates an example for the material-production stage. The unit process consists of other unit processes where data can be collected using different data-collection strategies, as discussed earlier in the chapter. Depending on the options chosen (primary or secondary and Options 1 to 4) and the scoring criteria, one can find a score for each

process included. The overall score for individual unit processes (such as raw materials, plant operations, or transportation) is determined using the options used in the data-collection strategy and emission factors or models used to develop the inventory results. Such scoring cards can be developed for major unit processes and included in the inventory report. The inventory report details the sources and models used in the development of inventory along with limitations and assumptions, which allows calculation of the score for individual raw materials or processes. Therefore, this approach can be seen as hierarchical in that data quality is evaluated starting from the upstream unit processes and moving to the downstream processes. An overall score can be evaluated using different approaches, such as simple averaging or weighted averaging.

Table 4-20. Example of data-quality evaluation for an aggregated-unit process in the material acquisition and production stage.

Process Type	Unit Processes	Data Source[1]	Data Coll. Option 1	Data Coll. Option 2A	Data Coll. Option 2B	Data Coll. Option 3	Data Coll. Option 4	Score[2,3]
Raw Materials	Binder production	Literature	-	✓	-	-	-	Good
	Aggregate production	Questionnaires	-	-	-	✓	-	Fair
	Polymer manufacturing	Commercial	-	-	-	-	✓	Poor
Plant Processes	Natural gas used in drying and heating aggregates	Questionnaire and commercial	-	✓	-	-	-	Fair
	Diesel used for internal transportation	Literature	-	✓	-	-	-	Fair
	Electricity used in conveyor belts, heating and storage	Literature	-	✓	-	-	-	Fair
Fuels and Electricity (indirect Inputs-Outputs)	Diesel	Commercial	-	-	-	✓	-	Fair
	Electricity	Custom Model	-	✓	-	-	-	Good
Transportation	Hauling trucks for upstream processes	Custom Model	-	-	-	-	✓	Fair
Overall Score	-	-	-	-	-	-	-	Good

1 Details of each data source and appropriate references should be described in the inventory report as shown with the example (see inventory report template provided in figure 4-6).
2 Score should be determined as part of the data-quality evaluation for each unit process using the scoring criteria (table 4-18) and assessment (table 4-19). This information for each unit process may be recorded in the inventory report template provided in figure 4-6.
3 Evaluation of score is not only dependent on data-collection option, but also on the emission factors (if used). The resulting decision for each unit process should be detailed in the inventory report for individual processes (using a hierarchical approach starting from the bottom).

An example of a data quality and uncertainty check for an EPD is shown in table 4-21 for an LCA preparing a nationwide cradle-to-gate EPD for ready-mix concrete.

Table 4-21. Data source and data-quality assessment for raw material supply module adapted from the industry-wide EPD for ready-mixed concrete (NRMCA 2014).

Material/Unit	LCI Data Source	Geography	Year	Data-Quality Assessment
Cement (lbs)	Update of portland cement, at plant (USLCI database). Modified to include upstream impacts of fuel and energy production	USA	2010	Technology: good. Process represents average cement production in the U.S. Time: Very good. Data is within 4 years. Geography: very good. Completeness: good. Data is based on an average of national production. Reliability: very good.
Fly Ash (lbs)	None, no incoming burden, only inbound transport was considered	N/A	N/A	N/A
Slag Cement (lbs)	LCI Slag Cement Manufacturing	USA	2003	Technology: good. Process models ground granulated blast furnace slag. Time: fair. Data is within eleven years. Geography: very good. Completeness: good. Reliability: good.
Crushed Aggregates (lbs)	Ecoinvent process: "Gravel, crushed, at mine" Ecoinvent 2.02, CLF PCR Default	EU	2004	Technology: good. Processes represent aggregate, with and without crushing. Dust emissions are estimated from limestone mining. Time: fair. Data is within ten years. Geography: fair. Processes model Swiss production (no U.S. process in USLCI database). Completeness: very good Reliability: very good. Data is verified by Ecoinvent.

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CHAPTER 5. IMPACT ASSESSMENT

5.0 Introduction

Life-cycle impact assessment (LCIA) translates the results of a life-cycle inventory (LCI) into measures of human or environmental impacts or damages. The translation of LCI results into impacts is conducted using a scientific approach that considers the impact chain (or cause-and-effect chain) of an environmental flow on humans, the natural environment, or natural resources (European Commission JRC 2010). LCIA assigns LCI results to impact categories; a life-cycle impact category indicator is selected for each impact category and the result is calculated. The collection of LCIA indicator results, referred to as the LCIA profile, provides information on the environmental issues associated with the environmental flows (inputs and outputs) of the product system.

LCIA is the third phase of the LCA. Its purpose is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance. ISO 14040 states that the purpose of the LCIA is "*understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product*" (ISO 2006a).

The process of performing an impact assessment is typically conceived of as a series of steps:

Step 1. Select the impact categories, category indicators, and characterization models that are to be included in the assessment.

Step 2. Classify each of the LCI results into the selected impact categories.

Step 3. Use a *characterization* model to translate the LCI results into impact category indicators.

Step 4. Consider the following optional steps:

a. Normalization. Calculating the magnitude of category indicator results relative to reference information.

b. Grouping. Sorting (and possibly ranking) the impact categories.

c. Weighting. Converting (and possibly aggregating) indicator results across impact categories using numerical factors that are based on value choices (note that original unweighted data should remain available).

d. Data-Quality Analysis. Development of a better understanding of the reliability of the collection of indicator results and the LCIA profile.

The LCIA may also include an iterative process of reviewing the goal and scope of the LCA study to determine whether the objectives of the study have been met, and then modifying the goal and scope if the LCA study results indicate that they are not achievable.

The flowchart shown in figure 5-1 can be used when defining the scope and approach for the impact assessment. Further guidance and discussion concerning each of the steps and the terminology included in this flowchart are presented in later sections of this chapter.

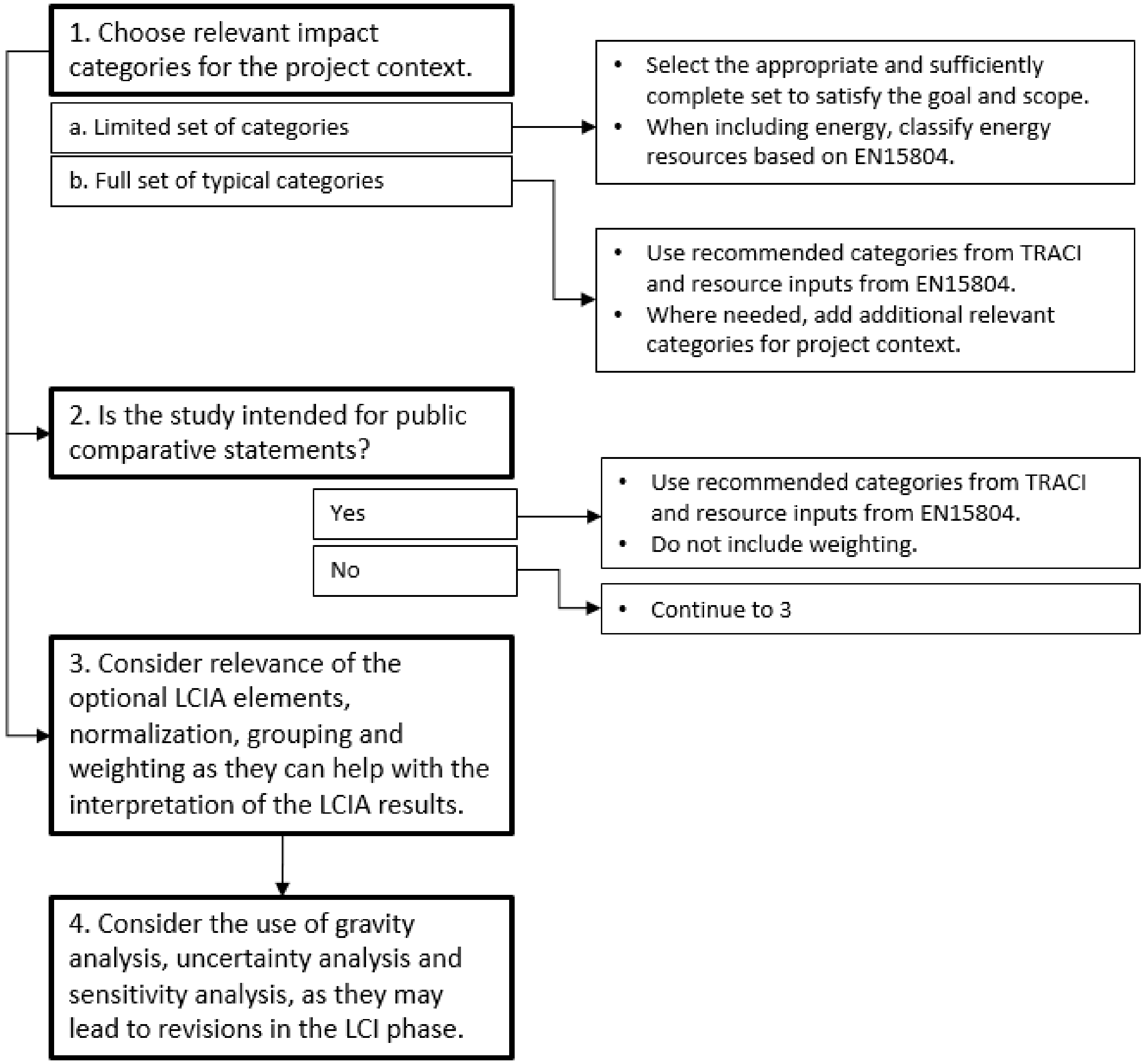


Figure 5-1. Flowchart of the impact assessment phase.

5.1 Guidance

This section provides guidance on the following impact assessment steps:

- Selection of impact categories and category indicators.
- LCIA data-quality analysis techniques.
- Selection of impact categories based on project context.

5.1.1 Impact Assessment Methodology

LCA looks at multiple impact categories, as opposed to approaches that only look at one flow or impact, like a carbon footprint or energy balance. This is one of the strengths of LCA. LCA is used to avoid unintended consequences and be informed about trade-offs; thus, the inclusion and evaluation of as many impact categories as is feasible is recommended.

Most pavement LCAs include energy use as a result from the inventory and global warming as a result from impact assessment as the primary reporting parameters, but the inclusion of a broader set of impact categories, such as those defined in the TRACI methodology (Bare 2012), is recommended. TRACI is the only impact assessment methodology that is regionalized for the U.S.

In addition to the impact categories included in TRACI (discussed later in this chapter), other impact categories or LCI results can be included if they are deemed useful or are required by the LCA goal or scope. This may be of particular importance for local, context-specific projects. When reporting on energy, the use of the resource input parameters listed in the EN15804 is recommended (CEN 2013). This includes the use of feedstock energy under the parameter "Use of nonrenewable primary energy used as raw materials."

The scope of impact assessment for EPDs is defined in the relevant PCRs. It is recommended that the PCRs follow the TRACI methodology and the EN15804 breakdown for energy. It is advisable to use a broad selection of impact factors when the main focus of the LCA is policy or specification recommendations. LCA that are to be used for network-level decisions or benchmarks may include a narrower selection of impact categories, depending on the study goal and scope and the anticipated use of the results.

Optional impact assessment elements, such as normalization, grouping and weighting, may be added when they can help with the interpretation of the LCIA results. Caution should be applied when presenting and interpreting results using these optional elements as most of the available methodologies include a subjective basis, which introduces value judgement.

5.1.2 Additional LCIA Data-Quality Analysis

Additional data analysis techniques and information may be needed to better understand the significance, uncertainty and sensitivity of the LCIA results to help determine whether significant differences are present, to identify negligible LCI results, or to guide the iterative LCIA process. Some of the most useful of these techniques are briefly described as follows:

- **Gravity Analysis** (e.g., Pareto analysis) is a statistical procedure that identifies those data having the greatest contribution to the indicator result. These items may then be investigated with increased intensity to ensure that sound decisions are made.
- **Uncertainty Analysis** is a procedure for determining how uncertainties in data and assumptions propagate through the calculations and how they affect the reliability of the LCIA results.
- **Sensitivity Analysis** is a procedure for determining the magnitude of the impacts of changes in data and methodological choices on LCIA results.

In accordance with the iterative nature of LCA, the result of this LCIA data-quality analysis may lead to revisions of the LCI phase.

5.1.3 LCIA for Comparative Assertions to be Disclosed to the Public

ISO 14044 requires that comparative assertions intended to be disclosed to the public use internationally accepted category indicators. In addition, ISO 14044 does not permit weighting to be used in LCA studies intended to be used in comparative assertions that may be disclosed publicly.

5.1.4 Project Context

The impact categories included in TRACI and the EN15804 represent commonly used categories in LCA. However, impact categories related to land and water use are gaining in importance, along with indicators related to renewable and nonrenewable resource consumption. In addition, spatial and temporal dimensions are gaining importance in impact assessment. Indicators related to land use, water use, and essentially all local pollutants (i.e., all pollutants excluding GHG and ozone-depleting gases) all benefit from spatially explicit modeling. Examples include:

- The land cover actually being occupied or transformed is an important measure for understanding the impacts of using or changing the land.
- The impact of water use is dependent on existing water stress and other local factors.
- The effects of local pollutants depend on the nature of the exposed populations or ecosystems, the fate and transport of the pollutants, and background emissions levels.

Temporally dynamic impact assessment methods have gained particular attention for global warming indicators (see, for example, work by Kendall [2012] and Levasseur et al. [2010]).

There are many obstacles to including both additional impact categories and undertaking spatially and temporally dynamic modeling, most of which are related to data quality and uncertainty. The reality of global supply chains and a reliance on LCI datasets that represent averages limit the capacity of LCA practitioners to undertake spatially and temporally explicit modeling. In addition, limitations in the environmental flows included in existing datasets may prevent the adoption of new impact categories.

Irrespective of the impact assessment methodology used for pavement LCA, context is always important, and its consideration is recommended as part of Interpretation, the next phase of LCA, which is discussed in chapter 6.

5.2 Commentary

LCIA is different from other techniques (such as environmental performance evaluation, environmental impact assessment and risk assessment, which are site and project specific) as it is based on a functional unit that covers the supply chain and life cycle of a product or system. These assessments can be used in parallel, as they have different goals and answer different questions. In many cases, the parallel use of these assessments can be synergistic, since LCIA may use information gathered by these other techniques.

LCIA consists of several elements that ISO 14040 defines as either mandatory or optional. The following sections discuss both of these types of elements.

5.2.1 Mandatory Elements of LCIA

Selection of Impact Categories, Category Indicators, and Characterization Models

ISO 14044 recommends a selection of impact categories that reflects a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration (ISO 2006b). LCIA can also include reporting of LCI results. This will typically include mass and energy flow data, but it can also include other topics, such as land use. For most LCA studies, existing impact assessment methodologies (which include a set of impact categories, category indicators, and characterization models) will be selected. However, in some cases, existing methodologies do not include impact categories, category indicators, or characterization models that fulfil the goal and scope of the LCA and, consequently, new methodologies have to be defined. This underscores the need for careful planning of the LCIA phase to ensure that the goals and scope of an LCA study can be achieved.

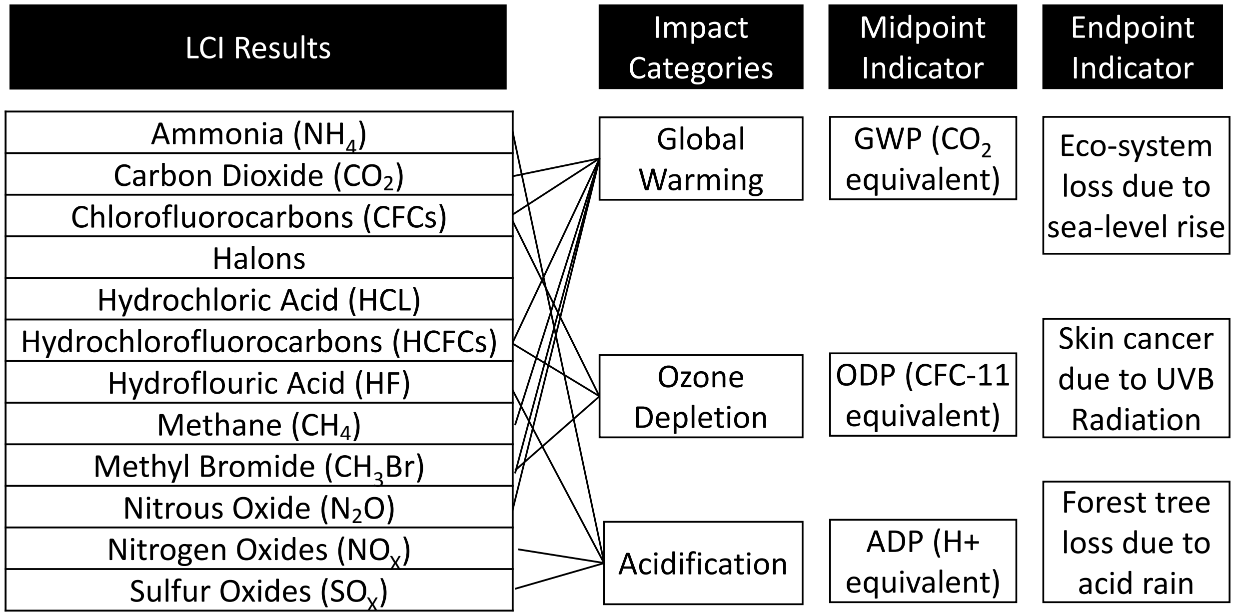
Characterization

Characterization is the identification and quantification of the relationships between the LCI results and the environmental impacts. For example, when a fuel is burned and carbon dioxide is emitted, the characterization defines whether, and by how much, the emissions contribute to global warming and the other selected impact categories. This is based on what is called a "characterization model," which is used to derive the characterization factors that are an expression of how the impacts relate to each impact category. For example, 1 kg of carbon dioxide relates to 1 kg of global warming potential (which has a unit of kg carbon dioxide). All other emissions are assigned characterization factors that express how they contribute to global warming relative to carbon dioxide's contribution. For example, methane has a high characterization factor because 1 kg of emitted methane contributes over 20 times more to global warming than does 1 kg of carbon dioxide. The characterization factor can be seen as an indicator of how much the impact indicator contributes to a specific impact category. The impact assessment evaluates all LCI results and, when a specific LCI result has a characterization factor associated with it, it will be added to the resulting impact category score.

Not all impact category indicators are created equally, as can be seen in figure 5-2. Indicators may be selected at any point along the relevant impact chain, with those indicators selected at any point before the endpoint referred to as "midpoint indicators." "Endpoint indicators," on the other hand, are those that model the full impact chain and consider impacts (i.e., damages) to humans and the environment (including environmental systems and natural resources). In general, the closer an indicator is to an endpoint, the more uncertainty is associated with the indicator.

For each indicator, the necessary components of the LCIA include:

- Identification of the categories of interest.
- Definition of the category indicator(s). These indicators may be midpoint or endpoint indicators. The category indicator can be chosen anywhere along the environmental mechanism between the LCI results and the endpoint(s), as illustrated in figure 5-2.
- Identification of LCI results to be assigned (classified) to the impact category, taking into account the chosen category indicator and the identified endpoint(s). Figure 5-2 illustrates the process of sorting (classifying) LCI results into impact categories and the impact category indicators that could be selected at a midpoint or at the endpoint.
- Identification of the characterization model and the characterization factors.



GWP = Global Warming Potential, ODP = Ozone Depletion Potential, ADP = Acidification Potential

Figure 5-2. LCIA steps with example impact categories and midpoint and endpoint indicators.

Table 5-1 provides a summary of the terminology that ISO 14044 uses to describe impact categories, category indicators, and characterization models.

Impact categories have different geographic scopes. Some impacts are local (e.g., some air quality measures, such as ground level ozone and particulates from traffic), some are regional (e.g., acidification due to the emission of sulfur dioxide from exhaust pipes), and some are global (e.g., global warming, where GHGs influence the global climate system, and resource depletion in relation to global availability/scarcity, for example the known oil reserves). When interpreting the results of the impact assessment, it is important to recognize the various geographic scopes, as pavement LCA projects are typically local and regional and could have very specific environmental constraints or conditions, such as air quality or noise concerns. ISO 14044 refers to this as the spatial characteristic of impact assessment.

Table 5-1. Examples of terms used in ISO 14044.

Term	Description	Example
Indicator	The environmental impact of interest.	Climate change.
LCI Results	A specific flow from the inventory, for example an emission.	Mass of a greenhouse gas per functional unit.
Characterization Model	The relation between an LCI result and the environmental impact of interest.	The Intergovernmental Panel on Climate Change's radiative forcing models.
Category Indicator	The unit used to measure the environmental impact.	CO_2e as defined by the cumulative radiative forcing (in units of W/m^2-yr) of a greenhouse gas over a defined time horizon relative to the cumulative radiative forcing of carbon dioxide (CO_2) over the same time horizon. This is a midpoint indicator.
Characterization Factor	The contribution of an LCI result to the environmental impact relative to the equivalency unit for the category indicator.	100-year GWP_{100} for each greenhouse gas (kg CO_2e/kg gas).
Category Indicator Result	The aggregated result from a combination of all LCI results and characterization factors.	Kilograms of CO_2e per functional unit.
Category Endpoints	What the actual impact is that we see takes place.	Species loss, human health effects, ecosystem loss, etc.
Environmental Relevance	The appropriateness of the how well the characterization model relates to the category endpoint.	Infrared radiative forcing integrated over time is a proxy for the total heat absorption and subsequent warming of the atmosphere caused by the addition of a quantity of gas to the atmosphere. Atmospheric warming leads to climate change through the warming of the atmosphere near the earth's surface.

Another characteristic of impact assessment is the duration of impact (time period). Some impacts have short-term effects (e.g., smog formation in the afternoon hours) while some have very long-term effects (e.g., global warming, where certain emissions today may have an impact that will last for centuries). ISO 14044 refers to this as temporal differentiation of the characterization model. Impact time periods can be different from the analysis period defined in the assessment goal and scope, but the inventory needs to accommodate the choices made for the impact assessment. For example, leachate from landfills could be modeled for a period of 100 years; that time period is not mandated anywhere, but is considered good LCA practice for most use cases.

There is also scientific uncertainty in the translation of an LCI result to an indicator based on some environmental mechanism. This uncertainty is caused by 1) the fate and transport of the substances and 2) the uncertainty in whether a category indicator sufficiently represents the category endpoint(s) of concern. Depending on the goal and scope of the LCA, it is advisable to reflect on this during the interpretation of the results.

The definition of the impact categories and the underlying science are typically addressed when LCA practitioners use recommended methods (e.g., the TRACI impact assessment methods) and the impact categories from the EN15804.

Impact Categories

There are numerous impact categories, which may relate to either inputs (e.g., reflecting the consumption of a resource) or outputs (e.g., reflecting the effects of a pollutant or group of pollutants). The impact categories included in TRACI are described below and are commonly used, but reflect a subset of those available to pavement LCA practitioners.

- **Acidification**. Acidifying pollutants are typically air pollutants (such as sulfur dioxide, SO_2) that are deposited on the earth's surface (water, soil, plants, buildings, etc.) through either wet or dry processes. Acid rain is perhaps the best known form of deposition of acidifying pollution. The process of acidification "is the increasing concentration of hydrogen ion (H+) within a local environment" (Bare 2012). Acidification can damage ecosystems and human-made systems, such as buildings and structures. These emissions show up in pavement LCA at almost any place where fuels are combusted (e.g., at the kiln used in the manufacture of portland cement clinker, or where diesel fuel is burned to power equipment).
- **Global Warming**. The EPA (2014) describes global warming as "the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of GHGs in the atmosphere. Global warming is causing climate patterns to change." Impacts from climate change include sea level rise, increased incidence and intensity of extreme weather events, and impacts on natural habitats, agriculture and human health. Sea level rise, extreme weather, and increased temperatures all have the potential to significantly impact infrastructure and other aspects of the built environment (Muench and Van Dam 2015). GHG emissions are primarily associated with the combustion of fuels (e.g., the combustion of gasoline by traffic during use), but can also occur during some production processes (e.g., during the calcination of limestone in the production of portland cement).
- **Ecotoxicity**. Ecotoxicity refers to the effect of chemicals released into an ecosystem, typically focusing on harmful effects to plant and animal life. Ecotoxicity depends on the quantity of pollutant released, fate and transport of the pollutant, its potency (i.e., dose response), as well as the environmental compartment (air, soil or water) to which it is released (Bare 2012). In addition, LCIAs will often report terrestrial and aquatic ecotoxicity separately, as the cause-effect chain depends heavily on whether terrestrial or aquatic systems are exposed. In pavement LCA, ecotoxicity is usually relevant for background processes that involve mining or specific chemistry processes.
- **Eutrophication**. Eutrophication occurs when nutrients are added to aquatic systems, causing increased growth in algae and plants. Key sources of nutrients include phosphorous and nitrogen fertilizers used in agriculture and runoff from livestock operations. Among other effects, increased algae and aquatic plant growth can eventually lead to reductions in dissolved oxygen in water bodies, causing fish to die off. The "dead zone" in the Gulf of Mexico is a well-known example of a water body area with depleted oxygen levels.
- **Human Health (Cancer and Non-Cancer)**. Though many different methods of modeling and characterizing human health effects have been proposed over the years, human health impacts (whether cancer or non-cancer related) typically assess the increase in morbidity caused by exposure to a pollutant. For example, USEtox, a characterization method used by the EPA's TRACI model, uses this measure to

assess human health impacts. USEtox has been harmonized across many methods and includes both global and continental scale modeling (Rosenbaum et al. 2008).

- **Human Health (Particulate Matter)**. Particulate air pollution includes particulates such as PM_{10} and $PM_{2.5}$ (particles of diameter 10 and 2.5 micrometers or less, respectively) and emissions that cause particulates to form through secondary reactions, such as NO_X and SO_X. These particulates have respiratory effects on humans and can lead to illnesses such as asthma, as well as to increased mortality rates. Like most pollutants that impact human health, the effects of these pollutants depend on the locations of emissions, fate and transport, and the exposed population (Bare 2012). Particulates are associated with the use of fuel (mostly diesel) in many processes in the pavement life cycle, but are particularly important in the use phase.
- **Ozone Depletion**. Stratospheric ozone protects the earth's surface from ultra-violet radiation. Some substances deplete stratospheric ozone and lead to increased pass-through of radiation, which can increase skin cancer, cause cataracts in humans and other animals, and damage plants and some human-made materials (Bare 2012).
- **Photochemical Oxidant Formation**. Photochemical oxidant formation refers to the reaction that leads to tropospheric ozone (O_3). Tropospheric O_3 forms through complex reactions between volatile organic compounds (VOCs) and nitrogen oxides (NO_X), in the presence of sunlight. Tropospheric O_3 damages living tissues in humans, animals, and plants, and can cause damage to human lungs and reduce plant productivity (Bare 2002). Because O_3 forms through complex interactions of a number of pollutants and environmental conditions, the effects of a particular atmospheric pollutant may be highly variable over space and time. Thus, regional modeling may be required to understand the O_3 formation potential of a given pollutant. Emissions from traffic during use are the most relevant contribution to ozone and smog formation.
- **Resource Depletion.** Resource depletion typically refers to the reduction in availability of fossil or nonrenewable resources, but may also include reductions in usable land and water. Increased land use is often an indicator of biodiversity loss and water use is an indicator of potential shortages or scarcity of water available for human and ecosystem uses (Bare 2002). The impacts of land use, water use and mineral resource depletion may vary greatly due to local conditions. Pavement LCA relates to resource depletion when fuels, oil or metals are used (e.g., for reinforcement).

Assignment of LCI Results to the Selected Impact Categories (Classification)

Assignment of LCI results to impact categories should consider the following, unless otherwise required by the goal or scope:

- Assignment of LCI results that are exclusive to one impact category.
- Identification of LCI results that relate to more than one impact category.
  - Distinction between parallel mechanisms (e.g., SO_2 is typically apportioned between the impact categories of human health and acidification).
  - Assignment to serial mechanisms (e.g., NO_x can be classified as contributing to both ground-level ozone formation and acidification).

Calculation of Category Indicator Results (Characterization)

The calculation of indicator results (characterization) involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category. This conversion is performed using characterization factors, and the outcome of the calculation is a numerical indicator. However, if LCI results are unavailable or if data are of insufficient quality for the LCIA to achieve the goal and scope of the study, either an iterative data collection or an adjustment of the goal and scope is required.

The usefulness of the indicator results for a given goal and scope depends on the accuracy, validity and characteristics of the characterization models and characterization factors. The number and types of simplifying assumptions and value choices used in the characterization model for the category indicator also vary between impact categories and can depend on the geographical region. A trade-off often exists between the simplicity and accuracy of the characterization model. Variation in the quality of category indicators among impact categories can influence the overall accuracy of the LCA because of differences in:

- The complexity of the environmental mechanisms between the LCI results and the category endpoint.
- The spatial and temporal characteristics (e.g., the persistence of a substance in the environment).
- The dose-response characteristics.

Impact Assessment Methodologies

While there are many impact categories and characterization models that can be combined in an LCIA, pre-existing impact assessment methodologies are often used in practice. An advantage of pre-existing methodologies is that they attempt to apply consistent methods across impact categories. A number of the more well-known methodologies include Ecoindicator99, CML, ReCIPE, TRACI and IMPACT2002+ (Goedkoop and Spriensma 2001; Jolliet et al. 2003; Goedkoop et al. 2009; Bare 2012). Extensive discussion of these and other impact assessment methodologies, as well as a comparison of methodologies, is available (European Commission JRC 2010). This chapter focuses on just two of these methodologies: TRACI Version 2.1, and IMPACT 2002+ (Jolliet et al. 2003; Bare 2012). In addition, the impact indicators suggested in EN15804 are also discussed. While EN15804 is not an LCIA, it does specify impact indicators and an LCIA method to be used and, thus, is relevant to this discussion.

The TRACI methodology and tool was developed by the EPA, reflecting conditions for the entire U.S. or for regions or states within the U.S.; it is the only LCIA methodology explicitly developed for the U.S. TRACI includes impact categories for acidification, ecotoxicity, eutrophication, fossil fuel depletion, global climate change, human health (cancerous, noncancerous and particulates), ozone depletion and photochemical smog formation. The methodology uses midpoint indicators, most of them in the form of equivalent or reference units (e.g., CO_2e [carbon dioxide equivalent] or CTUs [comparative toxicity units]). Table 5-2 describes the impact categories considered, the environmental compartments considered (air, water, and soil) and the impact category indicator units for the TRACI methodology.

Table 5-2. TRACI 2.1 impact categories (Bare 2012).

Impact Category	Media	Indicator unit
Acidification	Air	kg SO_2 eq
Ecotoxicity	Air, water and soil	CTU_{eco}/kg
Eutrophication	Air and water	kg N eq
Fossil Fuel Depletion	Raw materials	MJ surplus
Global Warming	Air	kg CO_2e
Human Health – Cancer	Air-urban, air-rural, freshwater, seawater, natural soil and agricultural soil	CTU_{cancer}/kg
Human Health - Noncancer	Air-urban, air-rural, freshwater, seawater, natural soil, and agricultural soil	$CTU_{noncancer}$/kg
Human Health Effects - Particulates	Air	kg $PM_{2.5}$ eq
Ozone Depletion	Air	kg CFC-11 eq
Smog formation	Air	kg O_3 eq

IMPACT 2002+ is unique among impact assessment methods as it combines both midpoint and endpoint categories and has both a regional and global scope. Midpoint categories *beyond* those listed for TRACI and included in IMPACT 2002+ are: ionizing radiation; land occupation; terrestrial acidification and nitrification; and a number of water use categories including water turbined, water withdrawn, and water consumed. The endpoints considered include human health, ecosystem quality, climate change (effects on life support systems) and resources.

Impact categories and indicators in EN15804 are selected specifically for EPDs of construction products and works in Europe (CEN 2013), and provide another relevant methodology. EN15804 is based on the CML impact assessment methodology and is defined in appendix A1 with mandatory characterization factors. Based on EN15804, the impact categories shown in table 5-3 should be included.

Table 5-3. EN 15804:2012+A1:2013 environmental parameters (CEN 2013).

Environmental Parameters	Unit
Global warming potential, GWP	kg CO_2
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11
Acidification potential of land and water resources, AP	kg SO_2
Eutrophication potential, EP	kg $PO^4{}_{3-}$
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl
Depletion of abiotic resources, elements	kg Sb
Depletion of abiotic resources, fossil fuels	MJ
Use of renewable energy primary energy, excluding renewable primary resources used as raw materials	MJ, net calorific value
Use of renewable primary energy resources used as raw materials	MJ, net calorific value
Total use of renewable primary resources	MJ, net calorific value
Use of nonrenewable primary energy, excluding nonrenewable primary energy resources used as materials	MJ, net calorific value
Use of nonrenewable primary energy used as raw materials	MJ, net calorific value
Total use of nonrenewable primary energy resources	MJ, net calorific value
Use of secondary material	Kg
Use of renewable secondary fuels	MJ
Use of nonrenewable secondary fuels	MJ
Input of fresh water*	m^3
Hazardous waste disposed	Kg
Nonhazardous waste disposed	Kg
Radioactive waste disposed	Kg
Further output material flows	Unit
Components for reuse	Kg
Materials for recycling	Kg
Materials for energy recovery	Kg
Exported energy	Kg

An example of a combined reporting of LCI results and LCIA results is included in the call-out box below.

Example of LCI and LCIA result reporting

EPDs can, but not necessarily include the reporting of both the LCI results and impact assessment results as required by the PCR. The table below shows an example of the findings from mean EPD results for the ready mix concrete industry. In this case, "national" refers to ready mix concrete of different strengths from more than 400 plants, against which a company can benchmark their own EPD results. The second table identifies the LCI results ("Inventory Metrics") and LCIA indicators used in the first table.

National average ready mix concrete EPD results (Bushi and Finlayson 2014).

Table E1-NRMCA U.S. National LCA Results

	Indicator/LCI Metric	GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
	Unit (equivalent)	kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	220.77	3.77E-06	1.01	0.11	13.41	1,792.7	1,777.9	14.9	1,713.3	0.44	0.14	0.13	0.26	0.31	2.04
	per m3	288.76	4.94E-06	1.32	0.15	17.54	2,344.8	2,325.4	19.4	2,240.8	0.57	0.18	0.16	0.34	0.41	2.67
3000 psi	per yd3	245.41	4.17E-06	1.11	0.12	14.41	1,962.8	1,946.6	16.3	1,720.4	0.46	0.14	0.13	0.26	0.31	2.04
	per m3	320.99	5.45E-06	1.45	0.16	18.85	2,567.3	2,546.0	21.3	2,250.2	0.60	0.18	0.16	0.34	0.41	2.67
4000 psi	per yd3	299.34	5.02E-06	1.33	0.14	16.60	2,338.6	2,319.3	19.3	1,740.9	0.52	0.14	0.13	0.26	0.31	2.04
	per m3	391.53	6.57E-06	1.73	0.19	21.72	3,058.7	3,033.5	25.2	2,277.0	0.68	0.18	0.16	0.34	0.41	2.67
5000 psi	per yd3	368.72	6.12E-06	2.16	0.21	25.50	2,821.9	2,798.8	23.2	1,741.3	0.60	0.14	0.13	0.27	0.31	2.04
	per m3	482.27	8.00E-06	2.83	0.27	33.36	3,690.9	3,660.6	30.3	2,277.5	0.78	0.19	0.17	0.36	0.41	2.67
6000 psi	per yd3	388.47	6.44E-06	2.25	0.21	26.41	2,966.6	2,942.3	24.3	1,810.7	0.62	0.15	0.14	0.30	0.31	2.04
	per m3	508.09	8.42E-06	2.94	0.28	34.54	3,880.1	3,848.3	31.8	2,368.3	0.81	0.20	0.18	0.39	0.41	2.67
8000 psi	per yd3	472.51	7.76E-06	2.59	0.25	29.81	3,554.9	3,525.9	29.0	1,831.5	0.71	0.15	0.14	0.30	0.31	2.04
	per m3	618.02	1.02E-05	3.38	0.32	38.99	4,649.7	4,611.7	37.9	2,395.5	0.93	0.20	0.18	0.39	0.41	2.67

LCIA indicators (used in the table above; Bushi and Finlayson 2014).

Benchmark Life Cycle Category Indicators and Inventory Metrics			
#	**LCIA Indicators**	**Abbreviations**	**Units**
1	Global Warming Potential (climate change)*	**GWP**	kg CO_2-eq
2	Ozone Depletion Potential*	**ODP**	kg CFC-11-eq
3	Acidification Potential*	**AP**	kg SO_2-eq
4	Eutrophication Potential*	**EP**	kg N-eq
5	Photochemical Ozone Creation/Smog Potential*	**POCP**	kg O_3-eq
	Inventory Metrics		
6	Total primary energy consumption	**PEC**	MJ (HHV)
7	Depletion of non-renewable energy resources*	**NRE**	MJ (HHV)
8	Use of renewable primary energy	**RE**	MJ (HHV)
9	Depletion of non-renewable material resources	**NRM**	kg
10	Use of renewable material resources	**RM**	kg
11	Concrete batching water consumption	**CBW**	m^3
12	Concrete washing water consumption	**CWW**	m^3
13	Total water consumption	**TW**	m^3
14	Concrete hazardous waste	**CHW**	kg
15	Concrete non-hazardous waste	**CNHW**	kg

5.2.2 Optional Elements of LCIA

Optional elements such as normalization, grouping, and weighting may be included as part of the impact assessment as long as their application and use is consistent with the goal and scope of the LCA and the use and substantiation for the use is fully transparent.

Normalization

Normalization is the calculation of the magnitude of the category indicator results relative to some reference information. The aim of the normalization is to better understand the relative magnitude of each category indicator result of the product system under study, and may assist in:

- Checking for inconsistencies.
- Providing and communicating information on the relative significance of the results.
- Preparing for additional procedures, such as grouping, weighting or interpretation.

Normalization transforms a category indicator result by dividing (or multiplying) it by a selected reference value. Some examples of reference values are listed below.

- Total inputs and outputs for a given area that may be global, regional, national, or local.
- Total inputs and outputs for a given area on a per capita basis or similar measurement.
- Inputs and outputs in a baseline scenario, such as a given alternative product system.

The normalization of the category indicator results can change the conclusions drawn from the LCIA phase. It may be desirable to use several reference systems to show the consequences of normalization on the outcome of the mandatory elements of the LCIA phase. A sensitivity analysis may provide additional information about the choice of reference data.

Grouping

Grouping is the assignment of impact categories into one or more sets, as predefined in the goal and scope definition, and it may involve sorting or ranking. Grouping is an optional element with two different possible procedures: either to sort the impact categories on a nominal basis (e.g., by characteristics such as inputs and outputs or global, regional and local spatial scales), or to rank the impact categories in a given hierarchy (e.g., high, medium, and low priority). Caution needs to be applied when reporting and interpreting results because ranking is based on value judgement. Different individuals, organizations, and societies may have different preferences; therefore, it is possible that different parties will reach different ranking results based on the same category indicator results or normalized category indicator results.

Weighting

Weighting is the process of converting indicator results of different impact categories by using numerical factors typically based on expert judgment. Caution needs to be applied when reporting and interpreting results because weighting is based on value judgement. It may also include aggregation of the weighted category indicator results. Weighting is an optional element with two possible procedures: either to convert the indicator results or normalized indicator results with selected weighting factors, or to aggregate converted indicator results or normalized results across impact categories.

Weighting steps are based on value choices and are not scientifically based. Different individuals, organizations, and societies may have different preferences; therefore, it is possible that different parties will reach different weighting results based on the same indicator results or normalized indicator results. In an LCA, it may be desirable to use several different weighting factors and weighting methods, and to conduct sensitivity analyses to assess the consequences of different weighting methods and value judgement on the LCIA results.

It is recommended that data and indicator results or normalized indicator results reached prior to weighting are made available along with the weighting results. This ensures that trade-offs and other information remain available to decision makers and to others, and that users can appreciate the full extent and ramifications of the results.

5.2.3 Limitations of LCIA

The LCIA addresses only environmental issues specified in the goal and scope. Therefore, LCIA is not a complete assessment of all environmental issues of the product system under study.

LCIA cannot always demonstrate significant differences between impact categories and the related indicator results of alternative product systems. This may be due to:

- Limited development of the characterization models, sensitivity analysis and uncertainty analysis for the LCIA phase.
- Limitations of the LCI phase (e.g., setting the system boundaries) do not encompass all possible unit processes for a product system or do not include all inputs and outputs of every unit process because there are cutoffs and data gaps.
- Limitations of the LCI phase that may be caused by uncertainties or differences in allocation and aggregation procedures (e.g., inadequate LCI data quality).
- Limitations in the collection of appropriate and representative inventory data for each impact category.

Another limitation is the lack of spatial and temporal dimensions in typical LCI results which introduces uncertainty, which varies with the spatial and temporal characteristics of different impact categories.

5.2.4 Resource Use and Feedstock Energy

An LCA registers what enters the human economy from nature and what leaves the human economy to nature. When a material is taken from nature, an LCA registers that as depletion of material resources *and*, if relevant, a depletion of energy resources. This means the materials that have energy in them register as depletion of an energy resource. This is relevant for a range of fuels and materials that are used for material products, such as plastics and asphalt binder. It also means that the use of nonabundant materials (e.g., iron ore that is used to make steel for reinforcement or bridge elements) adds to material resource depletion.

LCA distinguishes the following separate resource flows:

- Resource use: energy versus material.
- Resource renewability: renewable versus nonrenewable.
- Resource origin: from nature versus from the economy.

Examples of each combination of resource attributes are presented in table 5-4.

Table 5-4. Examples of resource use and LCA designation.

Resource	Examples	Renewable	Nonrenewable	From nature (primary)	From economy (secondary)*
Material	Wood for new wooden formwork; biodiesel or corn ethanol	X	-	X	-
Material	Reused wooden formwork, mulch	X	-	-	X
Material	Metal ores, oil for plastic and asphalt binder	-	X	X	-
Material	Steel scrap for rebar	-	X	-	X
Energy	Wood pellets for production forests for combustion in a cement kiln	X	-	X	-
Energy	Chips from used wood for combustion in electricity generation	X	-	-	X
Energy	Natural gas, fuel oil, diesel, etc.	-	X	X	-
Energy	Used tires for clinker production	-	X	-	X

*some LCA studies use the term “alternative” for secondary.

These distinctions are also represented in the requirements for reporting on resource use in EN15804. Table 5-5 shows the breakdown of resource use into different categories. Note that asphalt binder falls into the category of “nonrenewable primary energy resource used as a material.”

Table 5-5. EN 15804:2012+A1:2013 resource parameters (CEN 2013).

Resource input	Unit
Total use of renewable primary resources	*MJ, net calorific value*
• Renewable primary energy, excluding renewable primary resources used as raw materials	*MJ, net calorific value*
• Renewable primary energy resources used as raw materials	*MJ, net calorific value*
Total use of nonrenewable primary energy resources	*MJ, net calorific value*
• Nonrenewable primary energy, excluding nonrenewable primary energy resources used as materials	*MJ, net calorific value*
• Nonrenewable primary energy used as raw materials	*MJ, net calorific value*
Use of renewable secondary fuels	*MJ*
Use of nonrenewable secondary fuels	*MJ*

The treatment of feedstock energy in pavement LCA is a frequently discussed topic in North America. Feedstock energy is the energy content of a material. ISO 14044 defines feedstock energy as "*the heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value,*" and it includes a note that care is necessary to ensure that the energy content of raw materials is not counted twice (ISO 2006b). It is especially relevant to petroleum-based products that are used as materials rather than as fuel. For pavement LCA, this relates mostly to the use of asphalt binder, but also applies to the use of oil-based plastics and other materials. It turns out that the feedstock energy is one of the main drivers of the energy indicators that cover nonrenewable energy resources for asphalt concrete pavement.

It is LCA practice to include feedstock energy in the indicators that cover the use or depletion of nonrenewable energy resources. Some pavement LCAs have excluded binder feedstock energy from their analysis, which is not acceptable LCA practice. Other pavement LCAs have reported feedstock energy from binder separately from energy consumed in production. When reporting on energy, it is recommended to report different types of energy separately, as presented in table 5-5. Reporting feedstock energy separately for binder is particularly important when considering recycling, as the allocation of feedstock energy must be clearly defined to avoid double counting that can occur if it is not reported separately.

Additional LCIA Data-Quality Analysis

Additional analysis techniques and information may be needed to better understand the significance, uncertainty and sensitivity of the LCIA results. The need for and choice of techniques depend upon the accuracy and detail needed to fulfill the goal and scope of the LCA. As discussed previously, some of these techniques are: gravity analysis, uncertainty analysis, and sensitivity analysis. In accordance with the iterative nature of LCA, the result of this LCIA data-quality analysis may lead to revision of the LCI phase.

LCIA for Comparative Assertions to be Disclosed to the Public

ISO 14044 states the following regarding the use of LCIA to be used in comparative assertions intended to be disclosed to the public (ISO 2006b):

> *LCIA that is intended to be used in comparative assertions intended to be disclosed to the public shall employ a sufficiently comprehensive set of category indicators. The comparison shall be conducted category indicator by category indicator.*
>
> *An LCIA shall not provide the sole basis of comparative assertion intended to be disclosed to the public of overall environmental superiority or equivalence, as additional information will be necessary to overcome some of the inherent limitations in the LCIA. Value choices, exclusion of spatial and temporal, threshold and dose-response information, relative approach, and the variation in precision among impact categories are examples of such limitations. LCIA results do not predict impacts on category endpoints, exceeding thresholds, safety margins or risks.*
>
> *Category indicators intended to be used in comparative assertions intended to be disclosed to the public shall, as a minimum, be:*
>
> - *Scientifically and technically valid, i.e., using a distinct identifiable environmental mechanism or reproducible empirical observation.*

- *Environmentally relevant, i.e., have sufficiently clear links to the category endpoint(s) including, but not limited to, spatial and temporal characteristics.*

ISO 14044 requires the use of internationally accepted category indicators for use in comparative assertions that may be subject to public disclosure. In addition, ISO 14044 does not permit the use of weighting in LCA studies that are intended for use in comparative assertions that may be subject to public disclosure.

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CHAPTER 6. INTERPRETATION

6.0 Introduction

Interpretation is the final phase in an LCA study and consists of the following tasks (ISO 2006b):

- Identification of the significant issues based on the results of the LCI and LCIA phases of LCA.
- Evaluation, considering completeness, sensitivity, consistency and variability (uncertainty) of the results of those phases that may have impact on (and require amendments to) the goal and scope, inventory analysis, and the impact assessment.
- Development of conclusions, a statement of limitations, and recommendations.

The EN15804 standard requirements for the interpretation phase (CEN 2013) stipulate that it consider:

- Results of the study.
- Assumptions and limitations related to both methodology and data used for the analysis.
- Assessment of data quality, including variance from the mean results.
- Full and transparent disclosure of all value choices, judgments, and rationales.

Additional elements may be added to the interpretation framework as needed. When LCA is used for the development of EPDs, the interpretation requirements are prescriptive based on the requirements of the PCR. The interpretation phase answers the questions posed by the goal and scope of the study and makes recommendations based on those answers. Included with the answers and recommendations is consideration of the limitations and variability of the information used in the interpretation process and the sensitivity of the resulting answers and recommendations to those limitations and variability.

Interpretation is an iterative process, both within its own phase and within the entire LCA study. The iterative approach to the interpretation phase helps in developing, reviewing and revising the scope of the LCA and in making modifications and revisions needed in the LCI and LCIA phases to ensure that the results meet the goals of the study, including evaluating the nature and the quality of the data collected and calculation of impact indicators. The interpretation methodology should have been clearly described in the scope definition phase (ISO 2006b).

The LCA framework begins with the Goal and Scope Definition. Once that is developed, interpretation takes place by identifying significant issues and performing various checks for completeness, sensitivity, consistency, variability, and so on. Conclusions, limitations, and recommendations can then be drawn up, based on that interpretation work.

There are four major use cases for pavement LCA studies (see table 2-2) and different levels of study complexity (i.e., benchmarking studies and LCA studies with either small or full sets of indicators. The interpretation process shown in figure 6-1 applies to each of these cases and levels of complexity.

The flow of work for the interpretation phase is shown in figure 6-1.

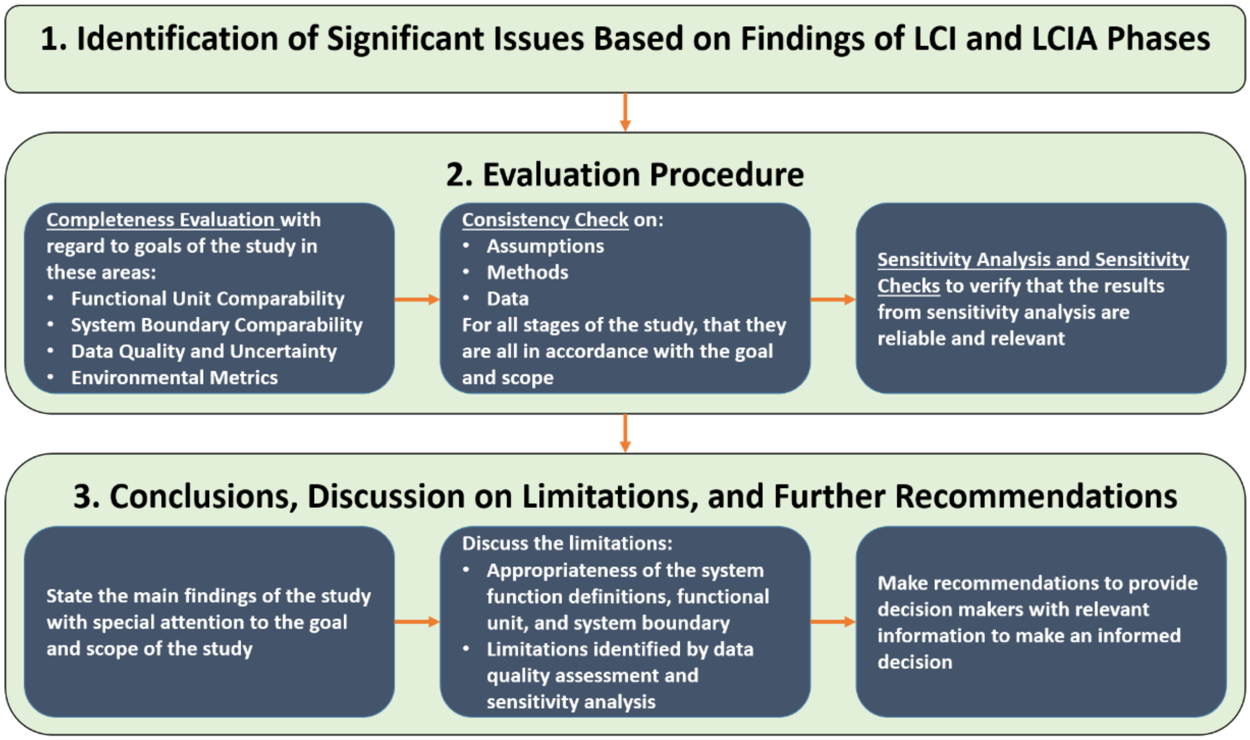

Figure 6-1. Flowchart of the process for conducting the interpretation phase of an LCA study.

With multiple sources of complexity in an LCA study, transparency is critically important in the interpretation phase since this is what decision makers and other intended target audiences are most interested in. Attention must be given to clear and concise presentation of the results in a manner appropriate to the target audience.

The rest of this chapter provides guidelines on how to conduct each of the interpretation steps identified in figure 6-1 and concludes in the discussion section with illustrative examples from studies collected from the literature.

6.1 Guidance

The following sections provide guidance on each step involved in the interpretation phase of an LCA study.

6.1.1 Identification of Significant Issues Based on Findings of LCI and LCIA Phases

As the first step in the interpretation phase, findings of the study's LCI and LCIA are organized and presented to identify the significant issues regarding the goal of the study. For benchmark studies the findings will be for the LCI only, while for other use cases it will be for the selected set of impact indicators. If presenting LCIA results, the interpretation phase should convey the fact that the results are indicators of potential environmental impacts and not the actual impact on the category endpoint, nor the safety margins and the risks involved (ISO 2006a).

The organization of the LCI and LCIA information should make use of graphics and summary tables to help illustrate areas where the highest impacts exist. The information should be presented in such a way that it allows decision makers to understand the results and to identify critical areas on which to focus. The information can be organized in tables or graphics according to the following types of elements, among others (ISO 2006b):

- Inventory flow type (emissions, energy and material resources, waste, etc.).
- Individual processes, unit processes or groups of processes.
- Life-cycle stages.
- Impact category indicators.

Within each of these organizational frameworks it is recommended that the LCI or LCIA results be presented in one or more of the following ways (ISO 2006b):

- **Contribution Analysis**, in which the contributions of life-cycle stages or groups of processes to the total result are examined by, for example, expressing the contributions as percentages of the total.
- **Dominance Analysis**, in which significant contributions are evaluated using statistical tools or other techniques, such as quantitative or qualitative ranking.
- **Influence Analysis**, in which the possibility of influencing the environmental issues is examined.
- **Anomaly Assessment**, in which, based on previous experience, unusual or surprising deviations from expected or normal results are observed; this allows for a later check and guides improvement assessments.

Combinations of these analyses are typically used, especially for studies aimed to improve environmental performance or studies aimed at informing decision makers regarding strategies and setting priorities. For example, results can be presented to show the contributions or dominance of different life-cycle stages, processes, emissions, etc. in a matrix along with influence information regarding the likelihood of being able to change each of those stages or processes. If probabilities of different levels of change have been identified as part of the LCI or LCIA phases, they can be used to calculate expected values of change for different types of life-cycle improvements or decisions.

For pavement LCA studies aimed at identifying opportunities to improve environmental performance of a product/service, the selected flows (benchmark studies) or performance indicators (LCA studies) in the goal and scope phase are typically presented for each life-cycle stage of the product or service so that the decision maker can identify the phases with the largest impact. Individual processes within each phase should generally also be shown, which may be further broken down by flows if needed to meet the goal of the study.

6.1.2 Evaluation Procedure to Ensure Completeness, Check Consistency and Analyze Sensitivity

Evaluation is the next step in the interpretation phase and includes checking for completeness, consistency and sensitivity, and any other checks or analyses called for in the goal and scope of the study. This is done to increase confidence in the results and to document the strength and reliability of the conclusions and recommendations.

Completeness

Completeness is defined as verifying whether the information from LCI and LCIA phases are sufficient for making conclusions in response to the goal and scope definition of the study.

Completeness should be checked by first verifying whether the scope identified for the LCI and LCIA phases has been met. If not, then the missing or incomplete scope should be completed. If the missing or incomplete LCI or LCIA scope cannot be completed, then it should be considered that the missing LCI or LCIA scope isn't necessary for satisfying the goal and scope of the LCA. The findings from the completeness check and justification for not completing the original LCI or LCIA scope should be documented as well as the reasons why the information is now considered unnecessary. If the missing LCI and LCIA scope cannot be completed, then the goal and scope of the study should be redefined or the study should be abandoned until the scope can be met. This process is shown in figure 6-2.

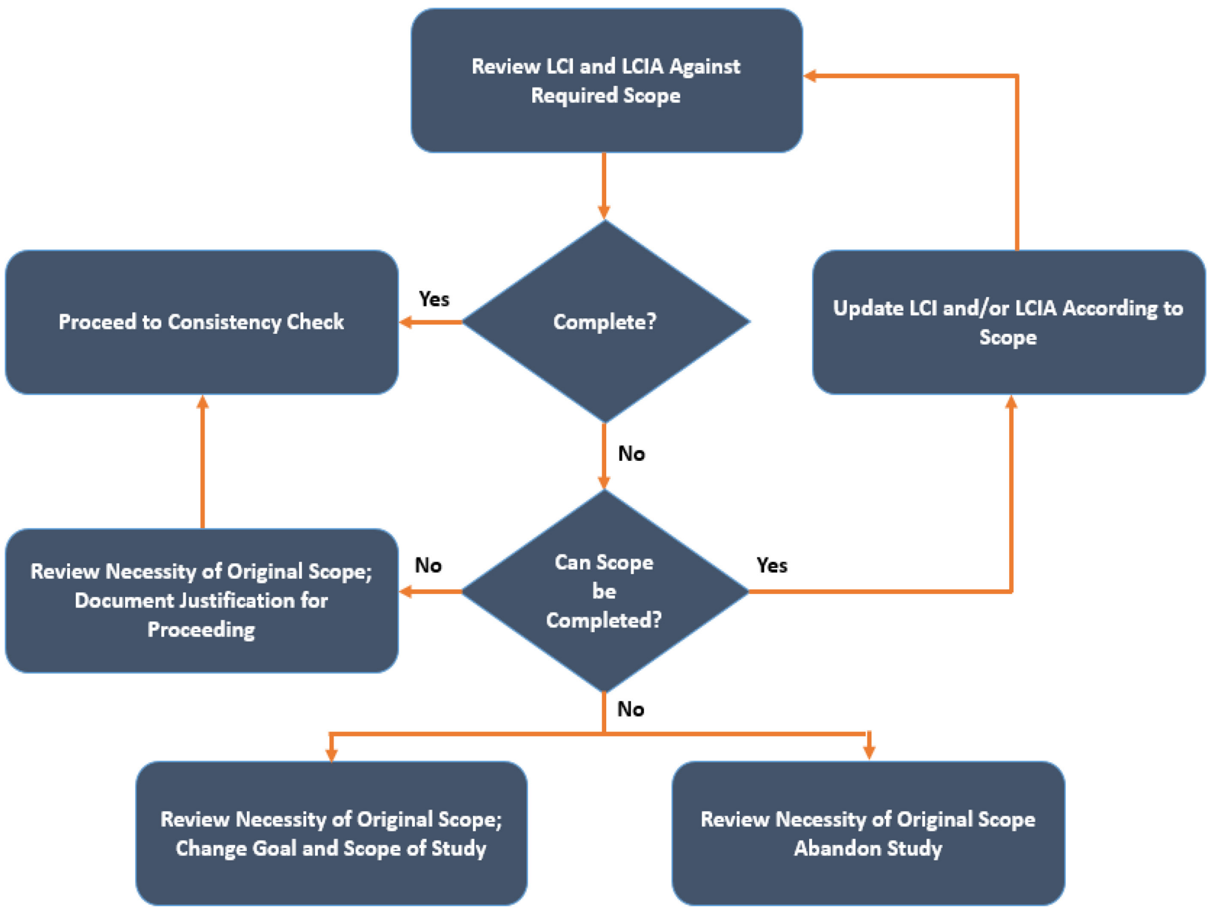

Figure 6-2. Flowchart for completeness evaluation.

Consistency

Consistency checks are conducted to verify that consistent assumptions, methods, and data used throughout different phases are all in accordance with the goal and scope of the study.

To perform the consistency check, the assumptions, methods and data developed from the LCI and LCIA should be reviewed against the stated assumptions, presumed methods and inventory and impact data requirements stated in the scope section of the study. Similar to the process shown in figure 6-2 for the completeness evaluation, any differences between the study's scoping document and the processes used for the LCI or LCIA or the results from those phases of the study should be assessed to determine whether it is desirable to move forward with the available information, perform additional work in the LCI or LCIA phases, change the goal of the study and update the scoping document, or abandon the study.

Consistency checks for pavement LCA studies at this time will often find problems with the availability of specific LCI data, as opposed to generic data or sometimes a lack of data, as well as the lack of appropriate impact assessment methods. For LCI data, the problems usually have to do with regional and temporal applicability, and a lack of multiple samples or sources to provide an indication of variability and uncertainty. The availability of primary data collected and reported by the owners of different processes, such as EPD data, will help substantially in solving this problem. A second (although less precise) alternative is improvement of data available in the literature. It is important that stakeholders, particularly those commissioning the studies, work with pavement LCA practitioners to identify and prioritize the types of data that will have the most influence on the results that they are relying on for decision making, and work to fill the other gaps that exist.

For the appropriateness of the impact assessment methods, problems may arise when specific local impacts are of interest while the impact assessment methods are less granular and sometimes global in nature. An example would be a specific air quality constraint in an urban setting dealing with health and respiratory issues, where the impact assessment methods are based on a regional or continental model that is not tailored to the specific local situation.

Sensitivity Analysis Check and Consideration of Uncertainty

Sensitivity checks are done to verify that the results from sensitivity analyses are reliable and relevant for making conclusions and providing recommendations. Sensitivity analyses should focus on methodological assumptions, for example for allocation and when scenarios are used.

The selection of the topics that are part of the sensitivity check should be informed by the results of the sensitivity analysis and uncertainty analysis, if performed in the preceding phases (LCI, LCIA). In other words, consideration should be given to (ISO 2006b):

- The issues identified by the goal and scope of the study.
- The results from all other phases of the study.
- Expert judgments and previous experience.

Depending on the goal and scope, these analyses can be qualitative (direction and trend based) or quantitative (specific). It is recommended to include sensitivity analyses and uncertainty analyses in the interpretation phase to confirm any conclusions.

The level of detail required in the sensitivity check depends mainly upon the findings of the inventory analysis (all studies) and the impact assessment (limited or complete LCA studies). When a pavement LCA is intended to be used in comparative assertions intended to be disclosed to the public, the comparison statements should include interpretation based on detailed sensitivity analyses.

Similar to the process shown in figure 6-2 for the completeness check, any differences between the sensitivity analysis requirements stated in the study's scoping document and the sensitivity analyses performed in the LCI or LCIA, as well as results from other phases of the study, should be assessed to determine whether it is desirable to move forward with the available information, perform additional work in the LCI or LCIA phases, change the goal of the study and update the scoping document, or abandon the study.

If the sensitivity analyses show that the LCI and LCIA results are reliable, relevant and sufficient to meet the goal and scope of the study, then the results from those studies should be used to show the apparent effects of the variability and uncertainty on the conclusions and recommendations.

6.1.3 Conclusions, Discussion on Limitations, and Further Recommendations

The final step in the interpretation phase is to report the findings and make recommendations for the intended audience of the study, while documenting the LCA study limitations. In this step the main findings of the study are reviewed again with special attention to the goal and scope definition of the study so that the recommendations will provide decision makers with relevant information to make an informed decision. The limitations in any phase of the study that are of interest to the decision makers should also be restated in this step.

The discussion on limitations included in the interpretation should consider the following in relation to the goal of the study:

- Appropriateness of the definitions of the system functions, the functional unit, and system boundary.
- Completeness check, the consistency check, data-quality assessment and the sensitivity analysis check.

It is recommended that the interpretation phase use a systematic approach in presenting the findings to meet the requirements of the study, as identified in the goal and scope definition phase. This approach should include a procedure to identify, check, evaluate, and present the findings and conclusions of the study.

Recommendations should address the needs of decision makers identified in the goal and scope statement and be based on the conclusions of the study, and should, if possible, reflect the certainty of those conclusions. The recommendations should also include any additional conclusions identified in the study that relate to the intended application of the study. Recommendations may also include potential research to address the identified limitations for future studies.

It has to be noted that future trends in LCA will likely influence the global harmonization of pavement LCA approaches and the comprehensiveness of interpretation such as the following (Rosenbaum 2014):

- New tendencies and expansions of classic LCA including, social LCA (S-LCA).
- Triple-bottom-line sustainability assessment (LCSA).
- Real-time and dynamic LCA.
- LCA for territories and organisations.
- Planetary boundaries.

6.2 Commentary

6.2.1 Identification of Significant Issues Based on Findings of LCI and LCIA Phases

This section includes examples of the first step in the interpretation phase: the organization and presentation of the findings of the LCI and LCIA of the study to identify the significant issues regarding the goal of the study. There are a number of graphical and tabular approaches for organizing the results of the LCI and LCIA phases to help identify significant issues for interpretation. The examples may be helpful in selecting the appropriate graphs and tables for new studies.

Presentation of the impacts by life-cycle stage helps decision makers interested in each of these impacts understand which stage they should focus their attention on. For example Table 6-1 shows the environmental impacts of different life-cycle stage (from "cradle" to "placement") of a cape seal surface treatment (Li et al. 2015). The results show that the material production stage is dominant for all indicators, and that the construction stage is also important for Photochemical Ozone Creation Potential (POCP).

Table 6-1. Environmental impacts of 1 lane-km of cape seal surface treatment (Li et al. 2015).

Life-Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (total) [MJ]	PED (NR) [MJ]	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (total) [MJ]	PED (NR) [MJ]
Material	5.03E+03	8.24E+02	4.03E+00	4.81E+05	4.75E+05	70%	52%	75%	94%	94%
Transport	6.53E+02	1.04E+02	2.09E-01	9.35E+03	9.35E+03	9%	7%	4%	2%	2%
Construction	1.49E+03	6.56E+02	1.17E+00	2.05E+04	2.05E+04	21%	41%	22%	4%	4%
Total	7.17E+03	1.58E+03	5.40E+00	5.10E+05	5.05E+05	100%	100%	100%	100%	100%

Note: GWP = global warming potential; POCP = photochemical ozone creation potential; PM2.5 = particulate matter less than 2.5 microns; PED (total) = total primary energy demand; PED (NR) = nonrenewable primary energy demand.

As an example of an LCA study conducted for strategic planning, figure 6-3 shows the annual CO_2e reductions compared to the option of "Do Nothing" for different groups of network sections categorized based on their traffic level, Passenger Car Equivalent (PCE), and different IRI trigger values.

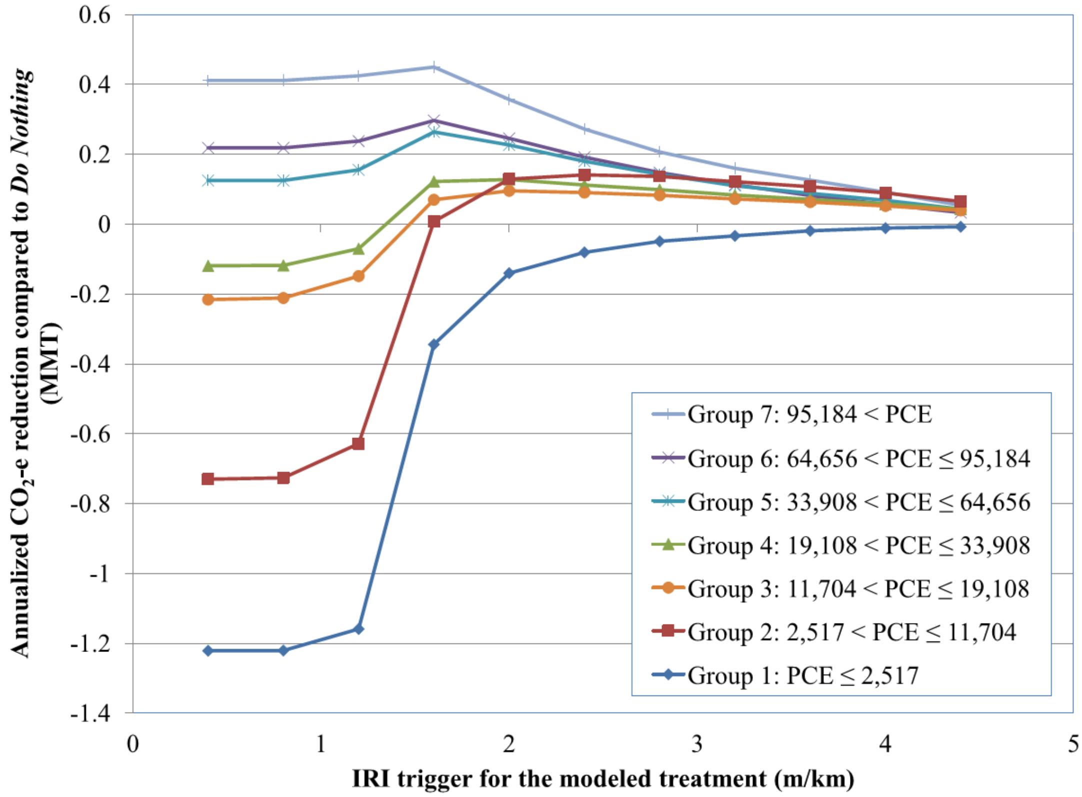

Figure 6-3. Annual CO_2e reductions compared to Do Nothing option for different classes of pavements within a network (Wang, Harvey, and Kendall 2014).

The study aims to identify optimal roughness level for different sections of the network that would result in the highest reduction in CO_2e emissions, considering the emissions added due to the maintenance activities and the emissions avoided by having smoother surfaces during the use phase. The graph shows that, for Group 1 sections that have low traffic, maintaining the sections at low roughness will not save enough emissions in the use phase to offset the emissions of the maintenance activities (i.e., CO_2e reductions are negative) while these numbers for Group 5 and above are always positive.

An example of the identification of major issues from the LCIA from a study of the impacts of pavement maintenance is shown in figure 6-4 (Wang et al. 2012). The goals of the study were to evaluate the net impact of performing pavement maintenance compared to not maintaining the pavement; this was done for different levels of traffic, different treatment options, and different levels of smoothness obtained at construction, and the scope included several different state highway sections. The figure shows energy savings (an impact indicator) by vehicles in the use phase and equivalent gasoline burned for replacing a small percentage of broken slabs in a concrete pavement followed by grinding versus leaving the pavement in a rough condition. Also shown are the same indicators and inventory data for the material production and construction stages. The results show that the pavement repairs have a significant impact on both the energy indicator and the inventory data in terms of equivalent gasoline burned (which will likely have an impact on air quality indicators), both of which were conveyed in the interpretation of the results. The results also show that the effect of constructed smoothness was important for high traffic areas, and that different estimates of traffic growth during the analysis period also affected the results.

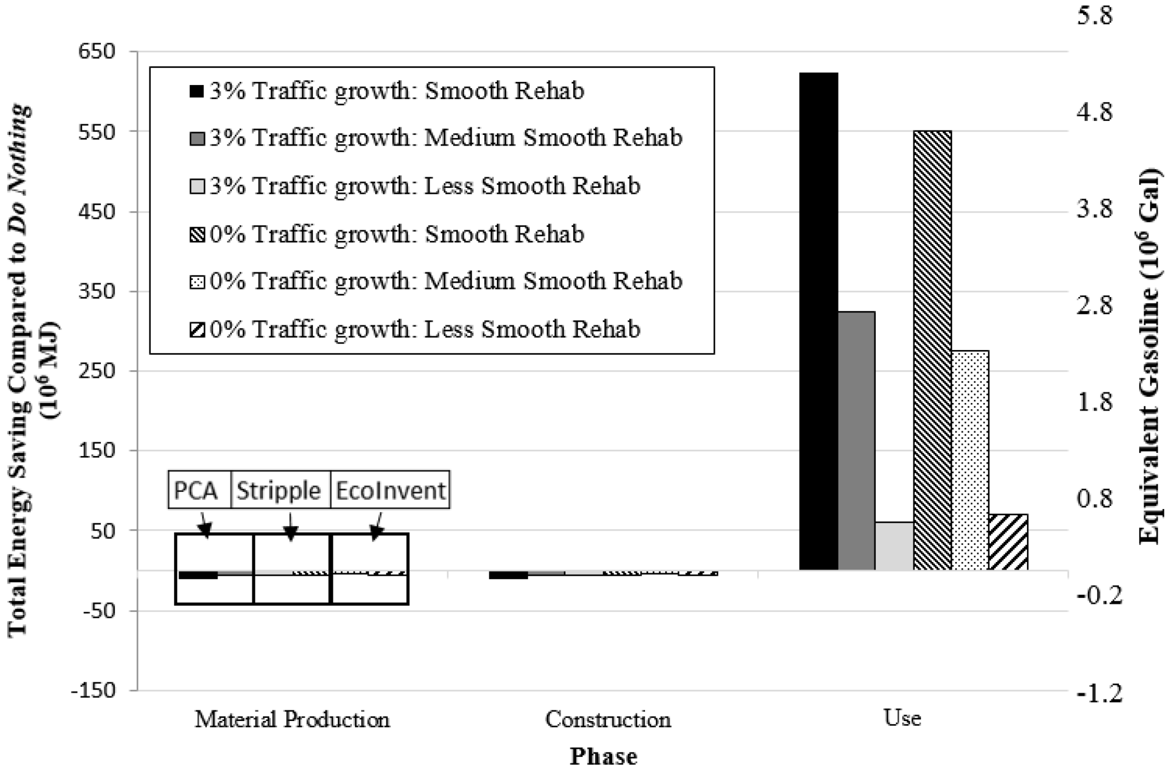

Figure 6-4. Analysis period energy savings compared to Do Nothing with Type III cement on LA-5 (Wang et al. 2012). (Note: diesel use converted to equivalent gasoline in terms of energy.)

Figure 6-5 shows another example, in this case a "spider web" diagram, taken from a comparison study of the materials and construction stages between roads built in different regions with different design methods and production processes to meet the same design traffic (Harvey et al. 2014). While for demonstration only, this figure provides a concise representation of the results of the study. Figure 6-6, from the same study, presents a bar diagram that shows for each case how each of the items in the design contribute to the final GWP of the section. This suggests to the decision maker the areas of each case with the highest impact and, thus, the areas where improvements could be made.

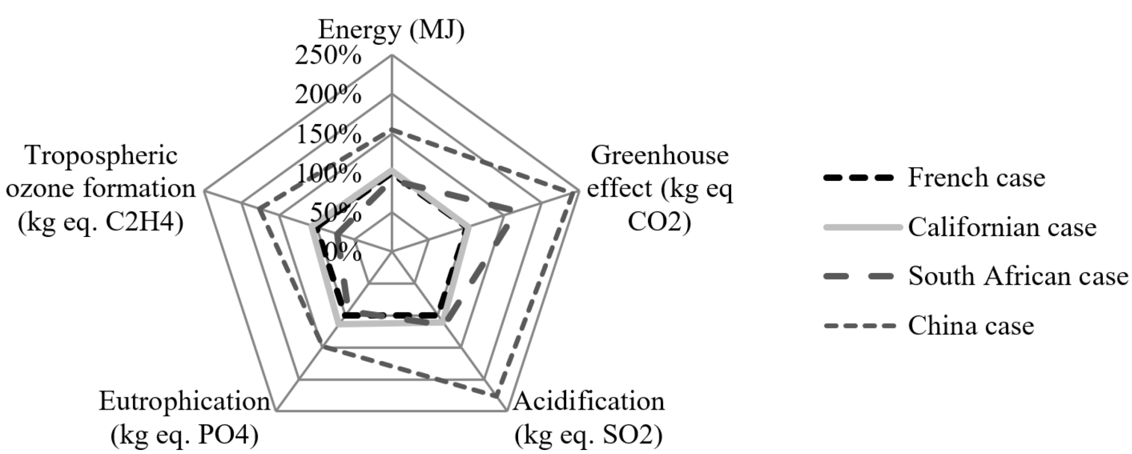

Figure 6-5. Spider web diagram showing comparison of major impact categories of pavement sections designed in different regions (Harvey et al. 2014). (Note: preliminary results for demonstration only.)

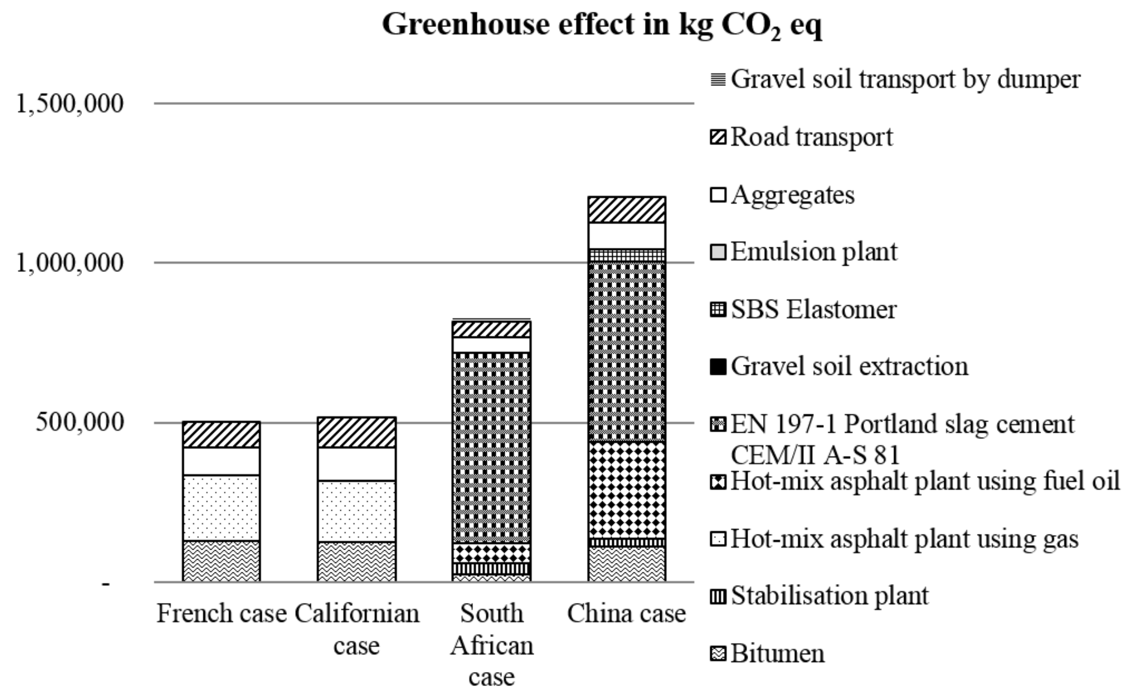

Figure 6-6. Global warming potential for each pavement section and contribution level of each of the section components (Harvey et al. 2014).

As an example of quantifying information on the environmental performance, table 6-2 shows the environmental impacts of producing 1 kg of crushed aggregate for a study which was focused on GWP, energy consumption, and air quality. Figure 6-7 shows items included in developing LCI and LCIA for the study based on local practice that can be considered in initial interpretation of results. This shows the assumed sources of energy for running the crushing plant based on average energy supply for a region, and should be accompanied by documentation of assumptions for flows that are smaller than the cutoff limits defined in the Goal and Scope. Figures like this can be used to show several types of information, such as flows for unit processes, the results of allocation, and the energy of material flows throughout a full life-cycle model. They are typically used to analyze the correctness of the software modeling and to demonstrate this in the report. Full disclosure of the assumptions in modeling phase with proper reporting and referencing increases the credibility of the results and the trust of the decision maker in the outcome of the study.

Table 6-2. Environmental impacts reported for 1 kg of crushed aggregate (Li et al. 2015).

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (total) [MJ]	PED (NR) [MJ]
Aggregate - Crushed	1 kg	3.131E-03	6.444E-04	1.555E-06	6.722E-02	4.831E-02

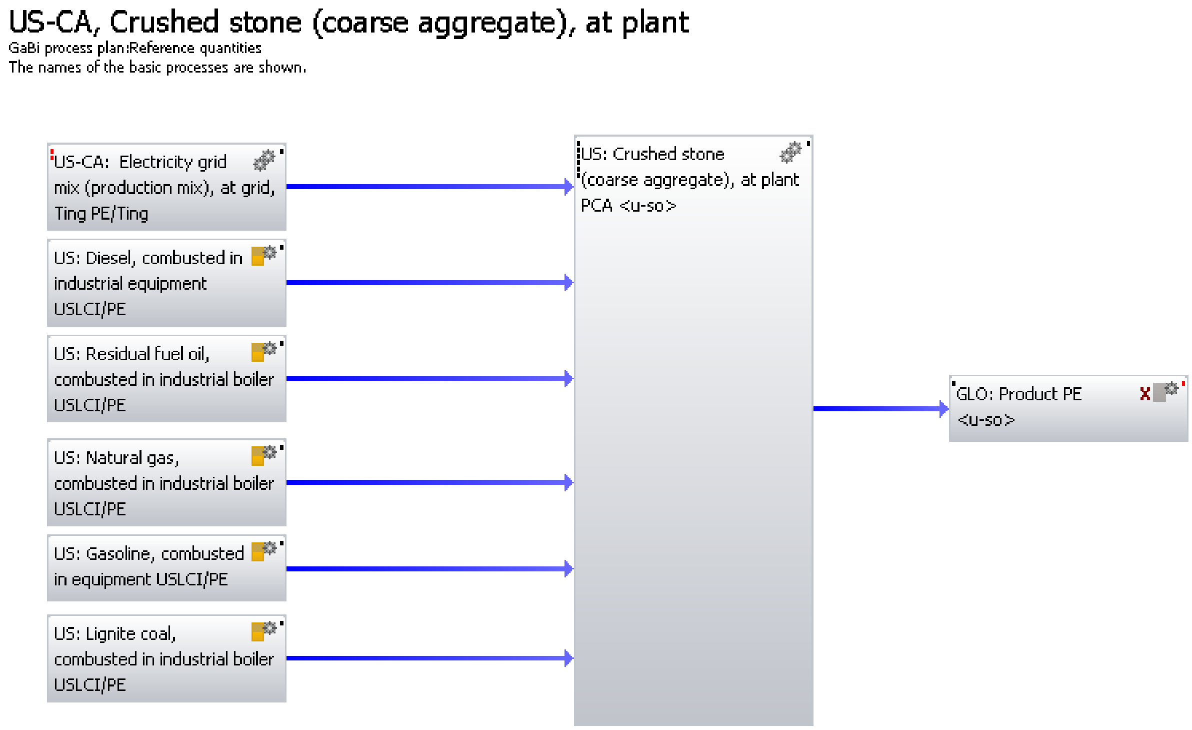

Figure 6-7. GaBi model developed to calculate LCI and LCIA of crushed aggregate production in California (thinkstep 2015).

Another example where the use case involved the quantification of information on the environmental performance is presented in table 6-3, which shows the results of an EPD published by Argos (Argos 2014). The single table provides a wide range of information regarding environmental performance and resource consumption of two of their products.

Table 6-3. EPD for two Argos products (Argos 2014).

Results Categories (Inventory/Impact Assessment Metrics)	**Unit**	**Mix Code 10014375 (4000 psi)**	**Mix Code 10019170 (8000 psi)**
Total Primary Energy Consumption	MJ	2646	3678
Concrete Batching Water Consumption	m^3	0.161	0.104
Concrete Washing Water Consumption	m^3	0.061	0.064
Total Water Consumption	m^3	21	17.4
Depletion of Nonrenewable Energy Resources	MJ	2612	3628
Depletion of Nonrenewable Material Resources	kg	2448	2494
Use of Renewable Material Resources	kg	0.764	1.030
Use of Renewable Primary Energy	MJ	33.9	50.4
Hazardous Waste	kg	3.36E-04	1.05E-01
Nonhazardous Waste	kg	0.731	0.726
Climate Change	kg CO_2e	432	633
Ozone Depletion	kg CFC-11 eq	5.61E-06	8.27E-06
Acidification	kg SO_2 eq	2.29	3.34
Eutrophication	kg N eq	0.068	0.094
Photochemical Ozone Creation/Smog	kg O_3 eq	32.9	45.8

6.2.2 Evaluation Procedure to Ensure Completeness, Check Consistency and Analyze Sensitivity

Completeness

An assessment of completeness in early pavement LCA studies by Santero, Masanet, and Horvath (2011) identified the following methodological areas for evaluating the completeness of pavement LCAs with regard to their goals: (1) functional unit comparability; (2) system boundary comparability; (3) data quality and uncertainty; and (4) environmental metrics.

An example of a completeness check is the one performed for the study used to produce figure 6-3. In this case, it was determined that sufficiently complete and accurate data were available and used for the following critical elements of the study identified in its goal and scope:

- All mix designs and construction scenarios were identified from a series of meetings with the concrete and asphalt industry organizations and were determined to be representative examples.
- Models were available for the relationship between vehicle fuel use and pavement roughness.
  - The models had been calibrated under a range of conditions and found to be reasonably accurate and precise.
  - Data were available to relate the population of vehicles and their operating conditions on the sections evaluated to the input variables needed for the models.
- Sufficiently accurate roughness performance models were available for the pavement treatments considered.

Consistency

The study that produced figure 6-4 also provides an example of a consistency check. In addition to the example concrete mix shown in the figure, similar results were obtained for a mix using calcium sulfoaluminate cement and for mixes with conventional dense-graded HMA and gap-graded, rubberized HMA. In each case, appropriate mix designs were obtained for each material, and thickness designs were developed using standard methods. Performance equations for roughness specific to the two types of HMA were used, and assumptions regarding performance of the two types of concrete mixes were stated along with a statement regarding the uncertainty of those assumptions.

In another example, the consistency checks for the study that produced figures 6-5 and 6-6 identified some major consistency issues; this led to the labeling of the results as "preliminary" and to subsequent recommendations for additional analyses (and particularly for better data) before taking any action based on the results. In that study, two major findings of the consistency check were reported:

- Important assumptions were made regarding traffic loading during the design life because of differences in traffic data, and in converting truck traffic axle load spectrum data into values used to determine pavement layer thicknesses. Load spectrum data were converted into equivalent repetitions of different types of standard single axles for use with the design methods of two countries, or were used in other ways specific to the design methods for the other two countries, which introduced potentially large inconsistencies in the comparisons of the resultant pavement structures. Assumptions were also made because one design method (China) had to account for a very high percentage of overloads due to relatively uncontrolled axle loading, while the other three had more control of overloaded vehicles. The result was that the pavement structures that were compared may not have been designed for the same truck traffic, which was a primary goal of the study.

- LCI data were used from France and California in the study because of lack of data for China and South Africa, with the only adjustments being consideration of electrical power and HMA plant fuel types. The relevance of these LCI data to other countries, and to different regions within the same country, indicates a potentially important lack of consistency.

It is interesting to note that the following methodological issues were not extensively considered in the available literature, yet may have a greater importance than some of the issues considered in previous studies:

- **Allocation Methods**, particularly for production of multiple products from one pavement-related process (e.g., asphalt production in a complex refinery) and inclusion of secondary products from other processes into pavement materials (e.g., fly ash and slag cement use in concrete and rubber use in asphalt).
- **Consistent System Boundary and Functional Unit Definitions**, which was considered in some literature in terms of different traffic levels, different climates, and inclusion or exclusion of different phases.
- **Regional Variability**, which was often difficult to assess without good regionally applicable data, although a few papers looked at adjusting existing data sets to reflect differences in fuel sources for plants, cement kiln types, and electricity mixes.
- **Temporal Variability**, which considers changes in practice over time, for example, changes in vehicle fleet fuel economy and fuel type and improvements in the efficiency of pavement materials production and construction processes.

Sensitivity Analysis Check and Consideration of Uncertainty

Identification and documentation of sources of uncertainty helps to identify steps to improve the quality of the inventory data and increase user confidence in the results of the study (GHG Protocol 2011). Uncertainty analysis is the systematic approach for quantifying the uncertainty produced in the results of the study due to a combination of model imprecision, input uncertainty, and data variability (ISO 2006a). Baker and Lepech (2009) argue that quantification of uncertainty in LCA results will help:

- Support informed decision making.
- Improve transparency.
- Increase competition for better quality data.
- Plan for information gathering exercises and identification of critical areas.

Types of Uncertainty

Variability exists in how to deal with uncertainty and how relevant it is for specific LCA studies. This section includes examples of uncertainty that are encountered in LCA literature and provides examples of how uncertainty is dealt with and reported in LCA studies.

In general, uncertainty can be divided into three categories as shown in figure 6-8 (Plevin 2010): lack of knowledge, variability in the data (due to heterogeneity across time, space or individuals), and decision uncertainty.

From another perspective, the GHG Protocol (2011) divides uncertainty into three groups: parameter uncertainty, scenario uncertainty, and model uncertainty. Table 6-4 summarizes these types and their sources. Parameter uncertainty is a measure of how well the data represent the actual process in the product inventory, while scenario uncertainty is due to methodological choices such as allocation methods and end-of-life assumptions. Model uncertainty is produced due outcomes from the inaccuracy of models to represent the real world.

In another paper, Baker and Lepech (2009) list main types of uncertainty as follows:

- Database uncertainty (e.g., missing or unrepresentative data).
- Model uncertainty.
- Statistical/measurement error.
- Uncertainty in preferences (modeling of preferences and value judgments).
- Uncertainty in the future physical system, relative to the designed system.

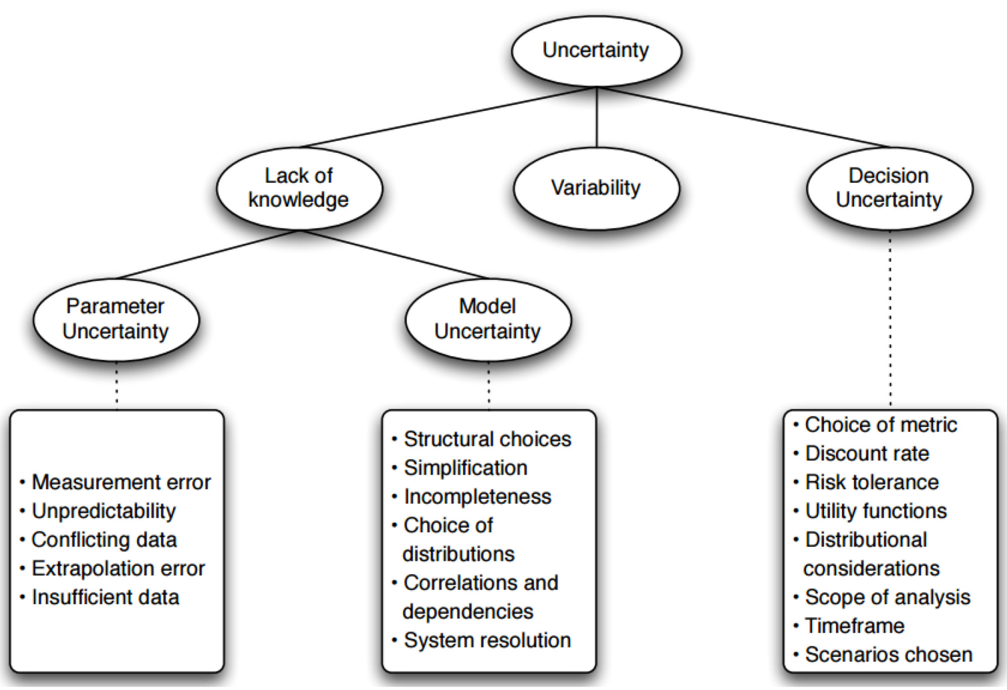

Figure 6-8. Types of uncertainty (Plevin 2010).

Table 6-4. Types of uncertainty and corresponding sources for global warming potential (GHG Protocol 2011).

Types of Uncertainty	Sources
Parameter Uncertainty	• Direct emissions data. • Activity data. • Emission factor data. • GWP factors.
Scenario Uncertainty	• Methodological choices.
Model Uncertainty	• Model limitations.

In terms of pavements in particular, as they are complex and long lived, uncertainty is an inherent part of any analysis conducted on them. Sources of uncertainty in pavement analysis include:

- Data variability.
- Input uncertainty.
- Model imprecision.

At the same time, there is also considerable uncertainty in models, methodologies, and the effects of system boundaries and functional units.

There is significant variability in the LCI data from multiple databases for the same process, and predicting the future always introduces uncertainty in the analysis. There is also uncertainty regarding the applicability of available data to the functional unit being evaluated if it is not primary data collected for the specific application and analysis period. The two major areas where the most uncertainty exists in pavement LCA studies are due to changes in location and time:

- Location.
  - Local practices in design, material production, construction, maintenance and at the pavement end of life vary significantly, making data obtained from one location not necessarily representative for other places.
  - Pavement performance is highly variable, and dependent on local construction quality, subgrade support conditions, materials types, traffic, and climate conditions, even with the exact same practice in design, material production, construction, and traffic loads.
- Time.
  - Pavement performance data over the life of the pavement are based on extrapolations and empirical data from existing pavements. These data are used to predict future performance which is not an easy feat. This is difficult for any pavement LCA but particularly difficult for new types of pavement or pavement practices that do not have established records of performance. Data from pavement management systems

can be used to provide performance histories for previous practice. Mechanistic-empirical (ME) pavement design and analysis methods, such as the AASHTOWare Pavement ME Design software and other ME approaches being used by state DOTs, are available and are continually being improved. They provide the best approach for estimating the performance of new types of pavement and materials as well as changes in pavement construction practice.

- Regulations for materials production, transport, construction equipment emissions, and improvements in energy efficiency for plant and equipment will likely change in the future; as a result, depending on their age, current data may reflect past rather than present or future practices and conditions.
- Traffic mixes, vehicle characteristics, configurations and technologies, and growth patterns are difficult to predict for the future.

Model imprecision is caused by the limits of current knowledge. Model uncertainty relates to data models used to develop inventory data, but also impact assessment models used in pavement LCA. Examples specific to pavement include, but are not limited to, mid-point indicators such as different emissions, energy use, resource use and how they relate to human toxicity, ecotoxicity, photochemical ozone formation, and other impact indicators for different regional and local conditions (Rosenbaum 2014).

Therefore, analysis of the uncertainty is needed for better decision making. An uncertainty analysis is the systematic approach for quantifying the uncertainty of the results of a life-cycle inventory analysis due to the combined impacts of model imprecision, input uncertainty, and data variability. The development of detailed models may reduce the uncertainties that arise from a lack of knowledge. In addition, scenario analyses of alternate theories or methods can test the robustness of study outcomes. The understanding that comes from uncertainty analysis should lead to recommendations for better data and models and follow up action for future LCA studies. It should also lead to caution when discussing the applicability of conclusions and recommendations beyond the limits of the data and models used in the study.

Analysis of Uncertainty

Figure 6-9 shows the general framework for treating uncertainties. The main approaches to address uncertainty are (Heijungs and Huijbregts 2004):

- **Scientific Approach**. Conducting more research to get more reliable data and reduce uncertainty.
- **Constructivist Approach**. Involving stakeholders, discussing and finally deciding on or voting on assumptions and selections.
- **The Legal Approach.** Relying on what authoritative bodies, like ISO or US-EPA, have decreed.
- **Statistical Approach**. Using methods from statistics, like Monte Carlo analysis or fuzzy set theory, to determine confidence intervals and other indicators of robustness.

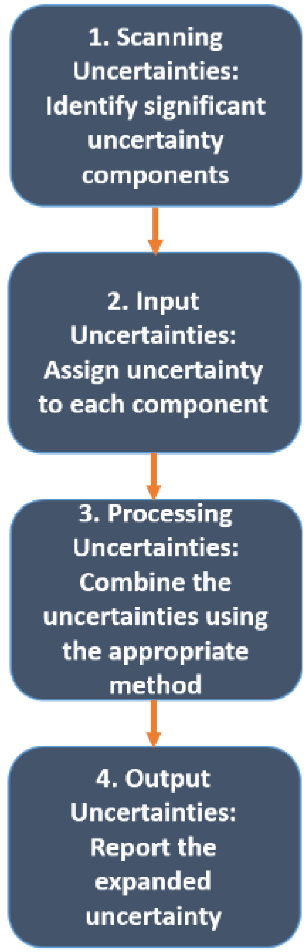

Figure 6-9. General framework for treating uncertainties.

The first three methods reduce uncertainty while the fourth method incorporates and clarifies uncertainty.

Problems encountered when addressing uncertainty arise on three sides (Heijungs and Huijbregts 2004):

- **Input Side**. Where are the uncertainties and how large are they?
- **Processing Side**. How to convert the input uncertainties into output uncertainties? Some of the available approaches are:
  - Parameter variation/scenario analysis.
  - Sampling methods (e.g., Monte Carlo simulation).
  - Analytical methods (consider mean and standard deviation and apply error propagation methods).
  - Consultation with experts.
  - Nontraditional methods, such as the use of fuzzy set theory.
- **Output Side**. How to communicate, report, and visualize the uncertain results?

GHG Protocol (2011) recommends using an iterative process for tracking and evaluating the uncertainty as shown in figure 6-10. The GHG Protocol recommends that LCA studies report qualitative statements on sources of uncertainty and methodological choices. Table 6-5 summarizes these recommendations.

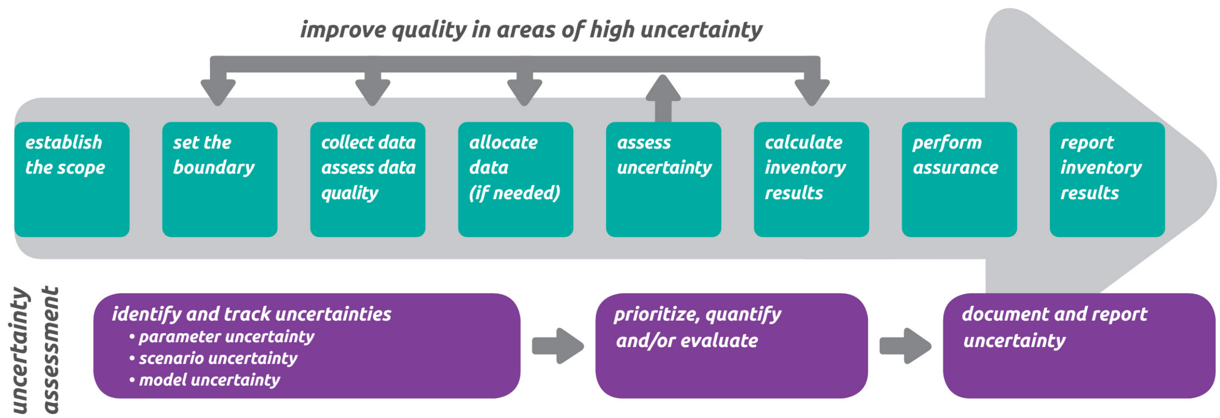

Figure 6-10. Process for tracking and evaluating uncertainty (GHG Protocol 2011).

Table 6-5. Example qualitative description of required uncertainty sources for global warming studies (GHG Protocol 2011).

Type of Uncertainty	Source of Uncertainty	Qualitative Description
Scenario	Use Profile	Describe the use profile of the product. If more than one use profile was applicable, disclose which method was used and justify the choice.
	End-of-Life Profile	Describe the end-of-life profile of the product. If more than one end-of-life profile was applicable, disclose which method was used and justify the choice.
	Allocation Method(s)	Describe any allocation problems in the inventory and which allocation method was used. If more than one allocation method was applicable, disclose which method was used and justify the choice.
	Recycling Allocation Method(s)	Disclose and reference which method was used (closed loop approximation method or recycled content method).
Parameter	Global Warming Potential Factors	List the source of GWP factors used.
Model	Model sources not included in scenario or parameter uncertainty	Describe the models, identify their published source, and identify areas where they may deviate from real world conditions.

PAS 2050 (BSI 2011) recommends using the Monte Carlo simulation approach to quantify the overall uncertainty of the carbon footprinting and identify relative hot spots. The objective would be measuring and minimizing uncertainty in the results and improving confidence in the decisions made based on the study. The Monte Carlo simulation approach requires knowledge of the distributions of important inputs and outputs in the LCI, and the variability of outcomes from the indicator calculations.

Table 6-6 presents typical strategies recommended by IPCC (2006) for dealing with different causes of uncertainties.

Uncertainty in data, inputs, and models can be considered by assessing the statistical variability in the data, and by performing sensitivity analyses considering different choices in methodology, system boundaries, functional units, and other choices made in the LCA in order to assess the influence of these factors on the results and their interpretation. Sources of uncertainty in pavement LCA can be divided into three categories, as shown in table 6-7, along with some suggested approaches for treating uncertainty (Harvey et al. 2011):

- Clearly define the functional unit, system boundaries, and goal to facilitate identification of sources of uncertainty.
- Conduct the study transparently by declaring the assumptions and data sources so that other researchers can improve upon the study as new data and methods become available.
- Conduct scenario and sensitivity analyses to test robustness of the model.

Table 6-6. Typical strategies for dealing with different causes of uncertainties (IPCC 2006).

Causes of Uncertainty	Evaluated Conceptualization and Model Formulation	Empirical and Statistical	Expert Judgement	Other Comments[1]
Lack of completeness	√	-	-	Have key components of the system been omitted? If so, what is the quantifiable or nonquantifiable effect on systematic error? Proper Quality Assurance/Quality Control (QA/QC) should help avoid this.
Model (bias and random errors)	√	√	√	Is the model formulation complete and accurate? What is the uncertainty in model predictions based on validation of the model? What is the estimate of model accuracy and precision based on expert judgment if statistical validation data are not available?
Lack of data	-	-	√	If data are lacking, can expert judgment be used to make inferences based on analogous (surrogate, proxy) data or theoretical considerations? May be related to lack of completeness and model uncertainty.
Lack of representativeness of data	√	√	√	-
Statistical random sampling error	-	√	-	e.g., statistical theory for estimating confidence intervals based on variability in the data and sample size.
Measurement error: random component	-	√	√	-
Measurement error: systematic component (bias)	√	-	√	QA/QC and verification may provide insight.
Misreporting or Misclassification	-	√	√	Proper QA/QC should help avoid this.
Missing data	-	√	√	Statistical or judgment-based approaches to estimating uncertainty because of nondetected measurements or other types of missing data

[1]It is *good* practice to apply procedures for QA/QC and verification prior to or combining with developing uncertainty estimates according to the guidance in chapter 6. The QA/QC and verification procedures provide a useful basis for preventing mistakes and for identifying (and preferably correcting) biases. Furthermore, QA/QC should prevent or help detect and correct misreporting and misclassification errors, and there should be iteration between uncertainty analysis and QA/QC if application of the uncertainty methods uncovers potential QA/QC problems.

Table 6-7. Treatments for uncertainty in pavement LCA (adapted from Harvey et al. 2010).

Types of Uncertainty	Recommended Treatment(s)
Data limitations, for example: • Geographic relevancy. • Variance in material production processes (due to geography or age of data).	• Data collection for improved LCA datasets. • Use of bounded ranges. • Stochastic methods.
Uncertainty in predicting the future, for example: • Future maintenance and rehabilitation activities. • Traffic patterns, growth, and vehicle fleets. • Technology advancement. • End-of-life use of materials with high recycled material content.	• Scenario analysis or sensitivity analysis.
Limits in knowledge, theory, or methods, for example: • Co-product allocation. • Impact models. • System-wide effects of on traffic network.	• Careful inclusion of complex processes and limiting the strength of conclusions based on those processes. • Scenario analysis of alternate theory or methods.

It is also recommended that a checklist be provided for consideration of major sources of uncertainty, either through sensitivity or statistical analyses. The checklist might include:

- System boundary and functional unit definitions.
- Allocation methods.
- Data and process uncertainty, including extent of aggregation (level of variation within a plant, and level of aggregation from plant to region) and seasonal variation, among other factors.
- Regional applicability.
- Temporal variability, considering likely changes in the future (which is particularly important for long analysis periods).

Assessment of the uncertainty in the data can be conducted by any of these methods:

- Qualitative assessment of data quality.
- Data Attribute Rating System (DARS) score for emission factors.
- Comparison of results with other literature or other regions.
- Use of upper and lower limits for values.
- Stochastic simulation (Monte Carlo simulation).
- Sensitivity analysis for important variables, e.g., allocation method, different technologies, data sources, etc.
- Computation of means and standard deviation values.

Examples of uncertainty analysis for pavement LCA using Monte Carlo simulation analysis are presented in Noshadravan et al. (2013). Results of scenario analysis using statistical parameters for similar cases is presented in Xu et al. (2014).

Below are some illustrations of where uncertainty has been considered in the pavement LCA literature and addressed through a sensitivity analysis of input parameters:

- Uncertainty regarding consideration of carbonation and albedo as a function of pavement structure in the use phase.
- Uncertainty in assumptions about preservation schedule, traffic pattern, overlay surface deterioration, and modeling of traffic.
- Uncertainty due to methodological choices, especially use of Economic Input Output (EIO) data versus process models for creating inventories.
- Sensitivity analysis of new technology diffusion and changes in traffic demand.
- Measurement uncertainty and application uncertainty (addressed by using probability distribution functions and stochastic analysis).
- Sensitivity analyses to understand the effects of various parameters on the MOVES emission estimation for vehicles using pavements in the use phase, e.g., temperature, calendar year, season, and time-of-day variation.
- Sensitivity analysis of: (1) traffic volume variability within each roadway classification, (2) timing of traffic closures, and (3) overall sensitivity to input parameters.
- Sensitivity analysis concerning the effect and the importance of the transport distances and the use of efficiently produced electricity mix.

An example of a sensitivity analysis for allocation is shown in figure 6-11. This study looked at allocation of environmental impacts in the oil refining process to asphalt binder used in pavements and other products. The study used an allocation method based on economic value of the products, but compared that allocation with allocations based on mass, volume, and energy content for the processes and products produced in different parts of the U.S. (referred to as PADDs) and the national average. The results show that the allocation method can have a significant effect on the energy consumption values used in the LCA.

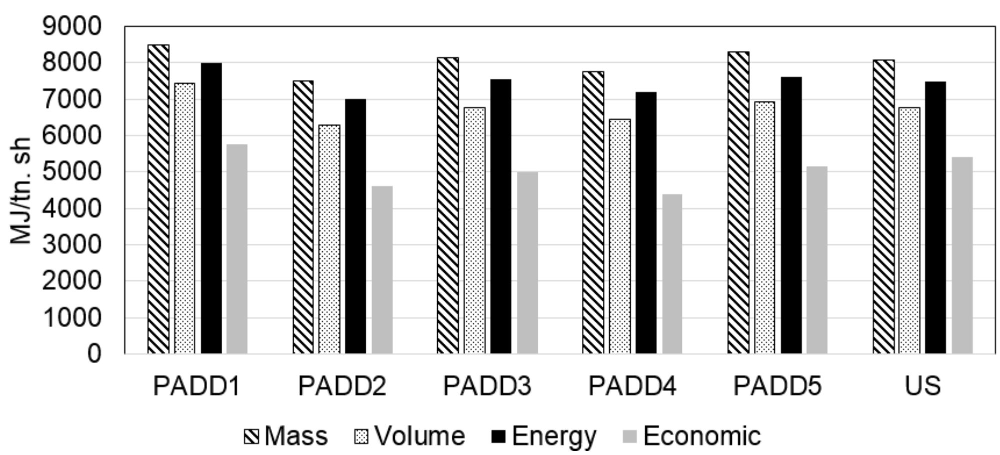

Figure 6-11. Energy consumption for binder production with various allocations (Yang 2014).

An example of a sensitivity check is illustrated by the use of different material production inventory sources (e.g., PCA, Stripple, EcoInvent) in the preparation of figures 6-2 and 6-3. The full sensitivity analysis for the study is shown in table 6-8 for each of the materials considered in the study.

Table 6-8. Overview of LCI sources for construction materials (corresponding to results shown in figures 6-2 and 6-3) (adapted from Wang et al. 2012).

Characteristic	EcoInvent	Stripple	Hakkinen	Athena	PCA	Others
Type	Commercial LCI	LCA Report	LCA Report	LCA Report	LCA Report	-
Location*	Global, Europe, Union for the Coordination of Transmission of Electricity, Switzerland	Sweden	Finland	Canada	United States	-
Year	-	2001	1996	2006	2006	-
Energy Value	MASS*	LHV	HHV	HHV	HHV	-
Capital Investment	Included	Excluded	Excluded	Excluded	Excluded	-
Electricity	Included	Included**	Included	Included	Excluded	-
Fuel	Included	Included***	Included	Included	Excluded	-
Crushed Aggregate	Yes	Yes	Yes	Yes	Yes	-
Natural Aggregate	Yes	Yes	Yes	Yes	Yes	-
Bitumen	Yes	Yes	Yes	Yes	No	Eurobitume USLCI
Crumb Rubber Modifier	No	No	No	No	No	Corti
Extender Oil	Yes	No	No	No	No	-
Recycled Asphalt Pavement	No	No	No	Yes	No	-
HMA Mixing Plant	No	Yes	No	Yes	No	-
Cement	Yes	Yes	Yes	Yes	Yes	-
Concrete Admixture	No	No	No	No	No	EFCA
Dowel Bar	No	No	No	No	No	World Steel Association
Concrete Mixing Plant	Yes	No	No	Yes	Yes	-

* Reported in mass of primary resource flows. Energy consumption is calculated by multiplying by HHV or LHV.
** Upstream profile of generating electricity is included. However, upstream profiles of producing fuels, which are required for generating electricity, are excluded.
*** Upstream profiles of producing fuels, which are combusted for transport equipment, are included.

Figure 6-12 summarizes the environmental burdens of crushed aggregates and natural aggregates from the different inventory sources considered in the sensitivity analysis for the study. Each of these sources was considered in later analyses to provide an assessment of sensitivity to the LCI data source.

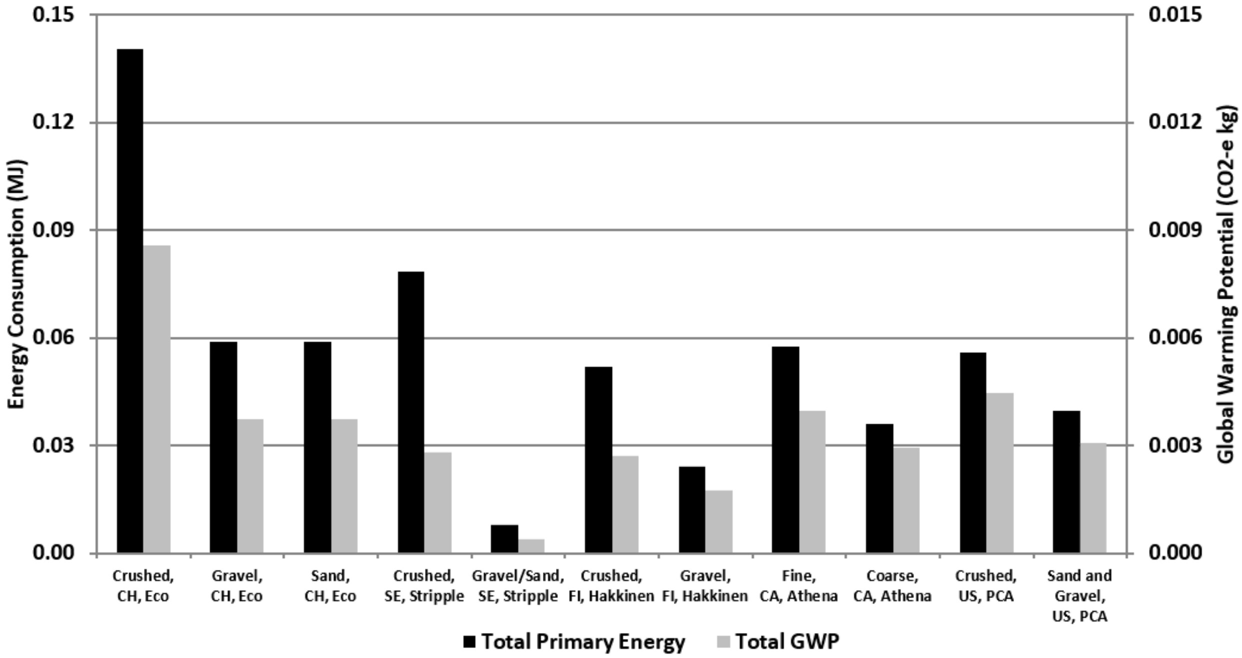

Figure 6-12. Aggregate production at quarry (1 kg) (Wang et al. 2012).

Figure 6-13 shows another example of a sensitivity analysis, in this case looking at the impact of asphalt binder content in HMA on the energy used (excluding feedstock) and GHGs emitted from producing the mix. These results are normalized to a baseline and show the results as a continuum, rather than as discrete values for the same thing from different inventories (as was done in figure 6-12).

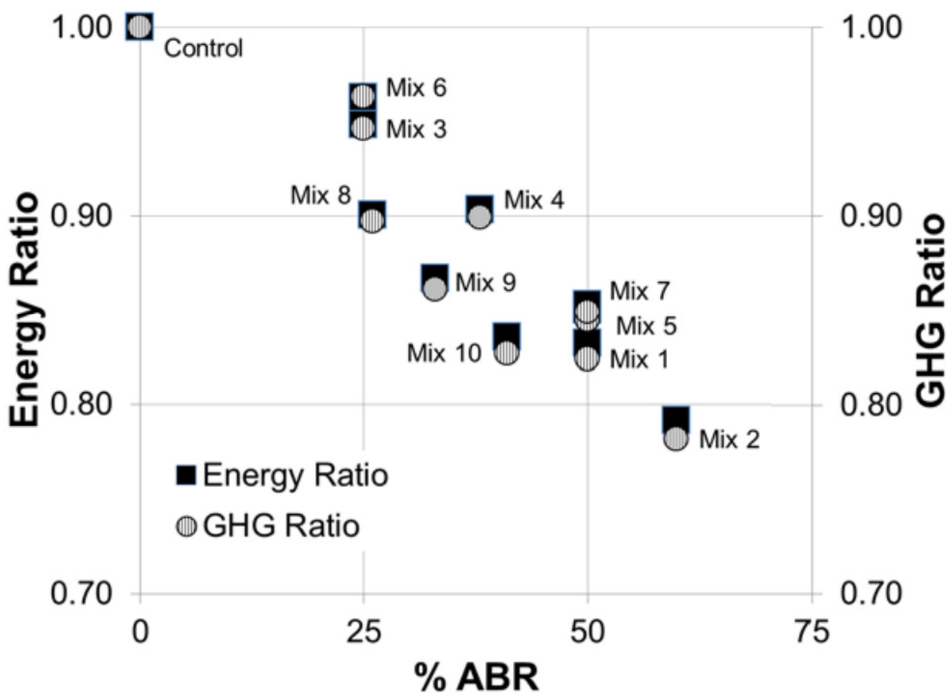

Figure 6-13. Normalized energy and GHG ratios without feedstock (Yang et al. 2014).

6.2.3 Conclusions, Discussion on Limitations, and Further Recommendations

An example of a conclusions and recommendations statement is taken from a recent report (Wang, Harvey, and Kendall 2014); that study had the goal of using a simplified version of the life-cycle assessment model developed by Wang et al. (2012) and applying it to the California state pavement network to evaluate strategies of medium thickness asphalt overlays placed on rough asphalt pavements and slab replacements and grinding applied to rough concrete pavement and their potential impacts on GHG emissions. The network was broken into different groups based on their traffic level in terms of equivalent numbers of passenger cars per day. IRI values for triggering treatments that can lead to the highest energy and GHG reductions were developed for each group. The study conclusion statement and recommendations (which included a reiteration of a limitation of the study) are as follows (Wang, Harvey, and Kendall 2014):

- *Traffic level has a substantial impact on the optimal IRI trigger. With optimal triggering, annualized CO_2e reductions of 1.38, 0.82, and 0.57 MMT can be achieved compared to the Do Nothing, the historical, and the current Caltrans IRI triggers over the 10-year analysis period. The cost effectiveness of these CO_2e reduction strategies is worse than those reported for other transportation sector CO_2e abatement measures when only considering fuel cost savings, but preliminary analyses indicate that pavement management can potentially be a cost-competitive measure to reduce GHG emissions if total road user cost is considered.*
- *Delaying M&R treatment when the IRI has reached the designated trigger can considerably reduce potential CO_2e reduction.*
- *Sensitivity analyses show that the constructed smoothness has a substantial impact on the results, and the analysis period does not have a substantial impact on the optimal IRI triggers. The potential for changes in cost effectiveness of treatment in light of recently improved construction smoothness specifications warrants future investigation.*

Future implementation of this work will include the expansion of the treatment options using an approach similar to this study, such as major rehabilitation/reconstruction treatments. An upcoming study will investigate the impact on fuel consumption from pavement structure change. With this expansion of scope, it is possible to develop a more comprehensive M&R schedule and policy to reduce CO_2e emissions over the pavement network life cycle.

An example of a limitations statement is available from Wang et al. (2012) as follows:

Important limitations of this study include the following:

- *These initial case studies only represent example sections, and application of this analysis to the network is work that remains.*
- *The materials datasets for the case studies used data from several sources outside California that were adjusted to California electrical energy supplies. Sensitivity analysis with the different data sets did not change the conclusions.*
- *All materials mix designs (taken from a series of meetings with the concrete and asphalt industry organizations noted in the acknowledgments) and construction were representative examples. There is a range of mix designs that could have been used for this analysis, these mix designs were provided by industry with the intention that they be typical.*

- *The method used to combine pavement characteristics (IRI and texture) and emissions models has not been validated, although the fuel economy models have been validated by Michigan State University.*

Another way of presenting limitations is in tabular format, as shown in table 6-9.

Table 6-9. Summary of major assumptions and sources used in the binder-model phase (Yang et al. 2014).

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

An example of a limitations statement from an EPD is shown below (Central Concrete 2013).

A summary of the limitations of this EPD include:

1. *This EPD does not report all of the environmental impacts due to manufacturing of the product, but rather reports the environmental impacts for categories with established LCA-based methods to track and report. Unreported environmental impacts include (but are not limited to) factors attributable to human health, land use change, water use in the upstream manufacturing process and habitat destruction.*
2. *This EPD reports the results of an LCA for 'cradle-to-gate' analysis and thus declarations are not comparative assertions. A comparative assertion is an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function. An EPD does not make any statements that the product covered by the EPD is better or worse than any other product.*

3. *In order to assess the local impacts of product manufacturing, additional analysis is required.*
4. *The product manufacturer has the option of declaring additional information about their product including conformance with any other sustainability certification programs that often have performance and prescriptive requirements that aim to capture environmental best practices that cannot be captured by LCA.*
5. *Life-Cycle Impact Assessment (LCIA) results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.*

EPDs of concrete mixes may not be comparable if they do not comply with this standard and data from this EPD. While EPDs can be used to compare concrete mixes, the data cannot be used to compare between construction products or concrete mixes used in different concrete products unless the data is integrated into a comprehensive LCA. For example, precast concrete, concrete masonry units and site-cast concrete all have different manufacturing processes whose impacts are attributed to different LCA phases. This precludes direct comparison between mixes used in these different products until all life-cycle stages are included.

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CHAPTER 7. CRITICAL REVIEW

7.0 Introduction

Critical review is defined as a "process intended to ensure consistency between a life-cycle assessment and the *principles* and *requirements* of the International Standards on life-cycle assessment," specifically with the *principles* described in ISO 14040 (ISO 2006a) and the *requirements* described in ISO 14044 (ISO 2006b). Critical review is one of the core elements of LCA that serves to verify whether an LCA has met the requirements for methodology, data, interpretation, and reporting in accordance with the ISO 14040 series of standards.

A critical review can neither verify nor validate the goals that are selected for an LCA by the study commissioner, nor can it verify or validate the ways in which the LCA results are used. Instead, a properly conducted critical review process ensures that:

- The methods used to carry out the LCA are scientifically and technically valid and are consistent with ISO 14044.
- The data used are appropriate and reasonable in relation to the goal(s) of the study.
- The data interpretations reflect the identified limitations and goal(s) of the study.
- The study report is transparent and consistent.

A critical review may facilitate the understanding of the LCA and can enhance its credibility through the participation of interested parties.

The flow diagram in figure 7-1 introduces the most relevant combinations of types of LCA and types of review. It includes requirements ("shall") and recommendations ("can").

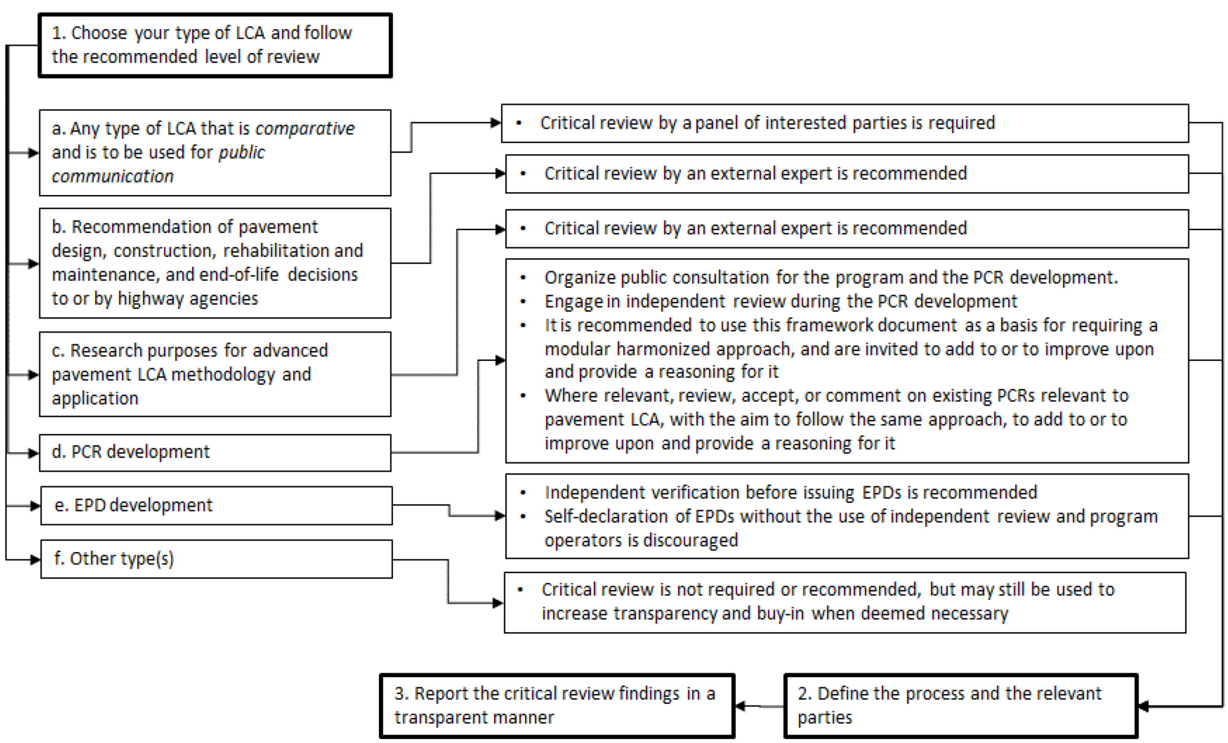

Figure 7-1. Critical review process.

7.1 Critical Review for LCA Studies

There are many options for conducting a critical LCA study review. The scope and type of critical review desired is defined in the scoping phase of an LCA (as discussed in chapter 3). According to ISO 14040, “the scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. The scope includes the type of critical review, if any” (ISO 2006a). The scope of the review should identify why the critical review is being undertaken, what will be covered and to what level of detail, what the process is, who needs to be involved in the process, and what level(s) of expertise are needed.

The critical review should ensure that the classification, characterization, normalization, grouping, and weighting elements are sufficient and are documented in such a way that the interpretation phase of the LCA can be carried out successfully. ISO 14040 states that “issues such as choice, modeling and evaluation of impact categories can introduce subjectivity into the LCIA phase. Therefore, transparency is critical to the impact assessment to ensure that assumptions are clearly described and reported” (ISO 2006a). ISO 14040 also specifically calls out the following elements of the LCIA in relation to the review process (ISO 2006a):

- LCIA procedures, assumptions and other operations within each element should be made transparent for critical review and reporting.
- The use of values and subjectivity (hereafter referred to as “value choices”) within each element should be made transparent for critical review and reporting.

ISO 14044 concludes the LCA process description with guidance on the interpretation phase by calling for the required inclusion of “the results from a concurrent critical-review process,” if one is conducted, in the final report (ISO 2006b). It specifies that “the review statement and review-panel report, as well as comments of the expert and any responses to recommendations made by the reviewer or by the panel, shall be included in the LCA report” (ISO 2006b).

There are different options for the critical-review process. ISO 14044 distinguishes between critical review by an internal or external expert, and critical review by a panel of interested parties, as described below.

7.1.1 Internal or External Expert

A critical review may be carried out by an internal or external expert. The internal or external expert should be familiar with the requirements of LCA and should have the appropriate level of scientific and technical expertise relevant to the product or service, in this case pavement. ISO 14025 specifies that independent experts retained for verification, whether internal or external to the organization, must not have been involved in the execution of the LCA or the development of the declaration, and must not have conflicts of interest resulting from their positions in the organization (ISO 2006c). A critical review by an external expert is recommended for pavement LCA studies that are intended:

1. To recommend pavement design, construction, rehabilitation and maintenance, and end-of-life decisions or policy changes to or by highway agencies.
2. For research purposes in support of advanced pavement-LCA methodologies and applications.

7.1.2 Panel of Interested Parties

A critical review may also be carried out by a panel of interested parties. In such cases, an external independent expert should be selected by the original study commissioner to act as chairperson of a review panel comprising at least three members. The chairperson should select additional independent qualified reviewers based upon the goals and scope of the study. The panel members should represent other interested parties affected by the conclusions drawn from the LCA, such as government agencies, nongovernmental groups, competitors and affected industries. The selection of review-panel members should consider their expertise in the scientific disciplines relevant to the important impact categories of the study, in addition to other expertise and interest.

7.1.3 Comparative LCA

A comparative LCA is used to inform decisions between different options that meet the functional performance requirement that is defined in the study goal and scope, e.g., when a producer wants to compare its product to a competitor's product. In a comparative study, results must be interpreted in the context of the equivalence of the systems being compared. Therefore, the scope of the study must be defined in such a way that the systems can be compared in an equitable manner. This implies that systems are compared using the same functional units and equivalent methodological considerations, such as performance, system boundaries, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment. Any differences between systems with respect to these parameters must be identified and reported. ISO also requires that an LCIA be performed for studies used in developing comparative assertions that are intended for public disclosure.

The use of LCA results to support comparative assertions raises special concerns and requires critical review because this application is likely to affect interested parties that were not involved in commissioning the LCA. ISO 14040 states that "in order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public" (ISO 2006a). This critical review is intended to prevent best-case representations of the LCA commissioning party and worst-case representation of the compared alternatives. However, the fact that a critical review has been conducted should in no way imply an endorsement of any comparative assertion that is based on an LCA study.

A critical review by a panel of interested parties is required by ISO 14040 for LCA studies that are of a comparative nature and are to be used for public communication. Good LCA practice includes the use of a conservative case for the approach by the commissioning party. An example would be the use of LCA for external communication of improvements in pavement life cycle as a result of design modifications by comparing environmental performance over time for the proposed project or design (using conservative performance assumptions) vs. that of previous projects or designs.

7.1.4 Review Process

The review process is not defined by ISO, but should result in a review statement that describes the compliance with the general ISO goals that are included in the introduction, a description of the reviewer or review panel and review process, and a summary of the most important comments, limitations or suggestions that the reviewer or the review panel deem to be of sufficient importance for sharing with the target audience. The reviewer(s) are allowed to make recommendations and add comments to the review statement to convey relevant topics that were defined during the review to future readers of the LCA report. A review is typically assisted by the use of a review template that tracks the comments, responses, and agreed-upon resolutions.

It may be necessary to share more details with the reviewer(s) than those that are included in the LCA report. These additional details can include, but are not limited to, such items as modeling details, detailed process inventory data for primary processes under control of the LCA study initiator, and additional LCA software output (such as process flow models). Depending upon the nature and sensitivity of the data to be disclosed to the reviewers, it may be necessary for the reviewers to sign confidentiality agreements regarding the content of the LCA.

It typically takes several rounds of review, comment and response before a review statement can be produced. The LCA report will typically include the review statement, the comments of the practitioner and any responses to recommendations made by the reviewer(s).

7.2 Critical Review for EPD and PCR

EPDs are, by definition, intended to be used in the market. EPDs defined on a common basis will warrant modularity, which will allow for use in more aggregated ways (e.g., a pavement EPD, where different materials are being used to construct the actual application). ISO recognizes this and has developed specific standards for EPDs, which are described in ISO 14025 as "providing quantified environmental data using predetermined parameters based on ISO 14040 and, where relevant, additional environmental information" (ISO 2006c). This means, by definition, that an EPD is based on an LCA.

The following conditions must be met in order to issue and publish an EPD:

- An EPD can only be issued by a Program Operator, defined by ISO 14025 as "a body or bodies that conduct a voluntary program for the development and use of Type III environmental declarations, based on a set of operating rules" (ISO 2006c).
- An EPD has to be based on a PCR document that consists of a "set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories" and that has received comments through a stakeholder process. It also must have been subject to a "PCR review process whereby a third party panel verifies the product category rules," where a product category group is defined as "any good or service that can fulfill equivalent functions."
- An LCA report based on this PCR has been independently reviewed for compliance with the ISO 14025, ISO 14040, and ISO 14044 standards, as well as the PCR document. Some EPDs are certified, but that is not mandated by ISO 14025.

7.2.1 Participatory Consultation

The process of developing environmental labels and declarations should include an open, participatory consultation with interested parties. Reasonable efforts should be made to achieve a consensus throughout the process. The interested parties for EPD programs may include, but are not limited to, material suppliers, manufacturers, trade associations, purchasers, users, consumers, nongovernmental organizations (NGOs), public agencies, and, when relevant, independent parties and certification bodies. Open consultation should take place and is strongly recommended, but this does not necessarily imply a public consultation. The program operator is responsible for ensuring that appropriate consultations take place to ensure credibility and transparency in the operation of the program. Competitors of the organization(s) developing the program or the PCR may be included in the open consultation.

> ***PCR Development Process***
>
> ***Select a Program Operator.*** *The Program Operator will own the PCR and will work with market parties that want to develop EPDs.*
>
> ***Establish an Industry Technical Working Group.*** *This working group will represent relevant industry members, but may also include interested stakeholders to add credibility and status to the work. The Working Group should possess the necessary relevant technical and environmental knowledge and should provide representation for all industries within the scope of the PCR.*
>
> ***Review Existing PCRs and Write Draft PCR.*** *Any relevant PCRs that may have been previously written in the USA, Europe or elsewhere should be reviewed. The Program Operator and Working Group will need to decide whether those reviewed PCRs can be modified to fit the US industry requirements or if the effort needs to be started from scratch.*
>
> ***PCR Review Committee.*** *Independent reviewers are to be chosen for this review. Potential reviewer sources include user-industries, academia, etc. A two-step approach is recommended, where a draft PCR is reviewed at the beginning of the process and a more developed final draft is reviewed prior to public disclosure.*
>
> ***Public Review.*** *The draft is sent out for comments. The Working Group will address the comments received.*
>
> ***Publication of the PCR.***

7.2.2 Harmonization

Any organization can be a program operator, which brings up the need for consistency between different program operators and PCRs. ISO mandates that program operators facilitate harmonization when developing a PCR for a product category by considering the adoption of readily available PCR documents in the same product category and in the appropriate market area. However, there may be valid reasons for developing PCR documents that have a different content than those that already exist. The justification for differing from an existing PCR should be based on the content of existing PCR documents and should not, for example, be based on the source of any particular PCR. The efforts undertaken to achieve harmonization, the outcomes, and the explanations for not using readily available PCR should be reported in the PCR document.

ISO 14025 has defined specific requirements for the PCR review and the EPD verification (ISO 2006c).

7.2.3 PCR Review

A PCR review is generally conducted by a third-party panel consisting of a chair and at least two additional members. The PCR document should include the results of the PCR review, as well as comments and recommendations made by the panel members. The PCR review aims to demonstrate the following:

- The PCR has been developed in accordance with the ISO 14040 series of standards and, specifically, in accordance with 6.7.1 of ISO 14025 on “contents of a PCR document” (ISO 2006c).
- The PCR fulfills the general program instructions, a document that describes the organization of the program and the adherence to the ISO 14025 requirements. It includes sections that relate to the process of creating and maintaining a PCR and the content of the PCR.
- The LCA-based data, together with the additional environmental information prescribed by the PCR, provide a description of the significant environmental aspects of the product. At a minimum, this includes the results of the impact assessment.

The combined competencies of the PCR review panel should include: 1) general background knowledge of the relevant sector, product, and product-related environmental aspects; 2) expertise in LCA and methodologies for LCA work; 3) awareness of relevant standards in the fields of environmental labeling, declarations and LCA; and 4) knowledge of the regulatory framework within the scope of the PCR. In addition, ISO 14025 requires the program operator to ensure a reasonable mix of interested party perspectives and competencies (ISO 2006c).

7.2.4 Independent Verification of the EPD

The independent verification procedure determines whether the environmental declaration is in conformance with ISO 14025, the program instructions, and current and relevant PCR. The verification aims to confirm whether the information given in the EPD accurately reflects the information in the documents upon which the declaration is based. The verification report is to be made available to any person, upon request.

ISO 14015 requires that the scope of the independent verification of data from LCA, LCI and information modules, and of additional environmental information, addresses of the following items, as a minimum:

- Conformance with the PCR, the ISO 14040 series, and the general program instructions.
- Requirements for the data evaluation include coverage, precision, completeness, representativeness, consistency, reproducibility, sources, and consideration of uncertainty in the data evaluation.
- The plausibility, quality, and accuracy of the LCA-based data.
- The quality and accuracy of additional environmental information.
- The quality and accuracy of the supporting information.

Product-specific data can be confidential because of competitive business requirements, proprietary information covered by intellectual property rights, or other similar legal restrictions (e.g., a patented or proprietary formulation for the composition of an engineered asphalt binder). Such confidential data are not required to be made public. The declaration typically only provides data aggregated over all relevant stages of the life cycle. Business data identified as confidential that are provided for the independent verification process must be kept confidential.

ISO 14025 specifies that independent verifiers, whether internal or external to the organization, must not have been involved in the execution of the LCA or the development of the declaration, and must not have conflicts of interests resulting from their positions in the organization. Program operators that own or develop PCRs relevant to pavement LCA are encouraged to:

- Use this framework document as a basis for requiring a modular harmonized approach, and are invited to add to or improve upon it (and provide a rationale for additions or improvements).
- Review, accept, or comment on existing PCRs relevant to pavement LCA, and similarly add to or to improve upon them.

ISO 14025 *requires* that program operators:

1. Organize a public consultation for the program and the PCR development.
2. Engage in independent review during the PCR development.
3. Include independent verification before issuing EPDs.

Self declaration of EPDs without the use of independent review and program operators is strongly discouraged.

7.3 References

International Organization for Standardization (ISO). 2006a. *Environmental Management - Life Cycle Assessment - Principles and Framework*. ISO 14040. International Organization for Standardization, Geneva, Switzerland.

International Organization for Standardization (ISO). 2006b. *Environmental Management - Life Cycle Assessment - Requirements and Guidelines*. ISO 14044. International Organization for Standardization, Geneva, Switzerland.

International Organization for Standardization (ISO). 2006c. *Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures*. ISO 14025. International Organization for Standardization, Geneva, Switzerland.

CHAPTER 8. REPORTING

8.0 Introduction

The project report is the systematic and comprehensive summary of the LCA study outcome. According to ISO 14044 (2006a), the data, methods, assumptions, results, and limitations are transparently presented in a sufficient level of detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. The report content and format should be consistent with the goal and scope identified at the beginning of the study. As the LCA is an iterative process, any changes made to the study goal and scope should be reported.

If the goal of the LCA is to publish an EPD, there are specific reporting requirements for both the EPD and the LCA report, which is often referred to as the background report. In that case, the project report can provide supporting documentation for the EPD.

According to ISO 14044 (2006a) and EN15084 (CEN 2013), the project report should be composed of the following general sections:

- **Summary**, providing a concise summary of the study with motivation, background, LCA methodology, and results.
- **Introduction**, consisting of background information and general motivation for the study.
- **General Requirements and Considerations**, is for LCA reports not intended to be disclosed to public, not for EPDS, or do not include comparative assertions.
- **Additional Requirements and Guidance for Third-Party Reports and EPDs**, including general aspects, goal and scope elements, inventory analysis, impact assessment, and results and interpretation and follows a specific format. These requirements must be followed when dealing with comparative LCA studies to be disclosed to the public, in particular.

The results and conclusions of the LCA should be reported in an adequate form to the intended audience. It is good practice to include an upfront summary aimed at informing the target audience of the study by presenting the main conclusions, recommendations, and limitations.

The project report may exclude sector or product specific information as confidential content. While it is recommended to publish a full report for public communication, it is permissible to leave out the confidential content that would be left out of other public documentation as well. However, confidential information must be made available to the LCA reviewers as part of a review process, when requested.

8.1 Flow of Work

The flow of work to prepare the final LCA report is shown in figure 8-1. This includes key procedures for preparation of an LCA report, which corresponds to the chapter organization, and in accordance with the ISO 14040 and 14044 guidelines. According to this, a final LCA report is composed of two major sections including an introduction and reporting of LCA related elements. For studies that are comparative assessment and are intended to be available to public, additional requirements should be regarded.

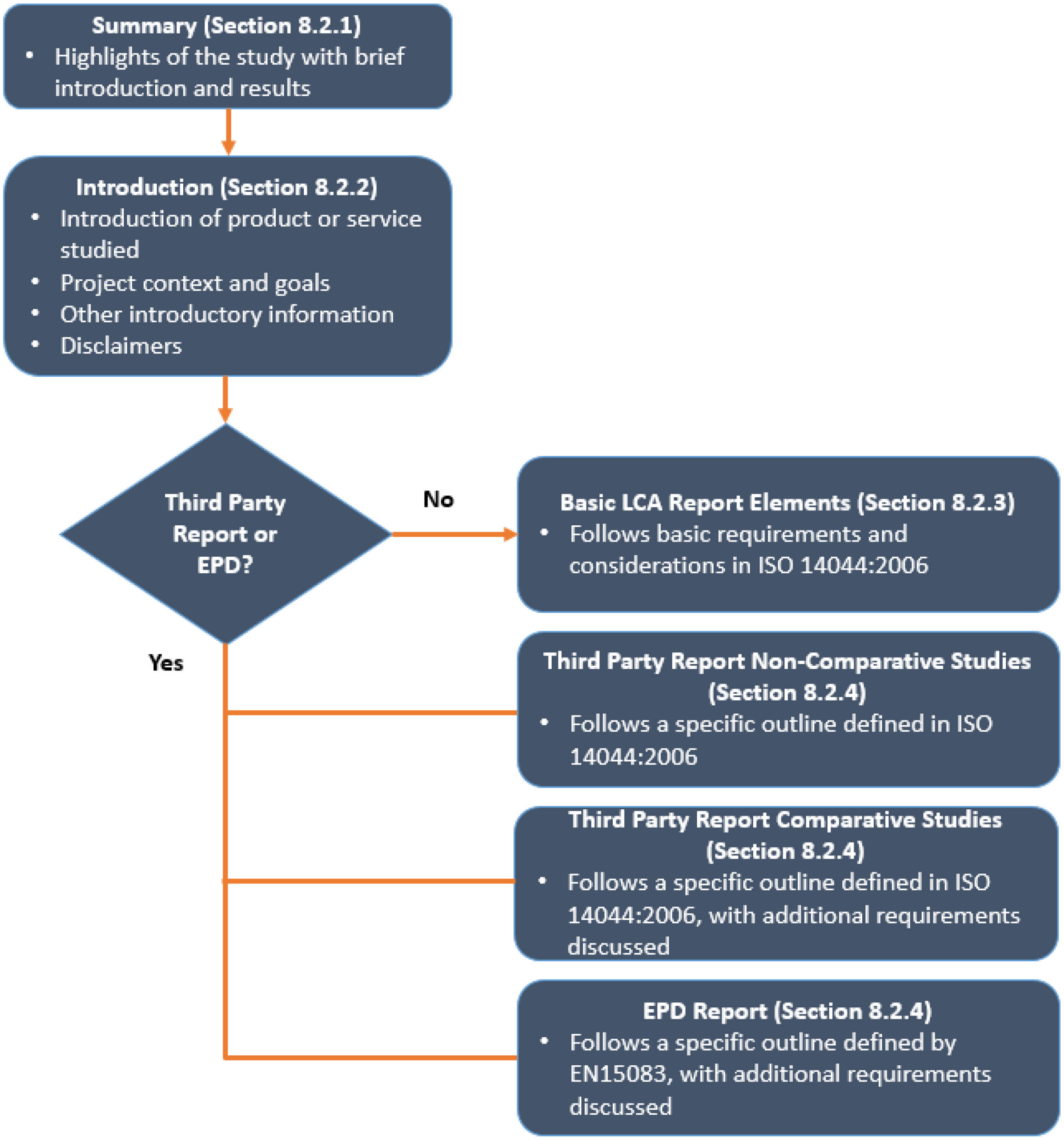

Figure 8-1. Flow of work and key procedures for reporting.

8.2 Guidance

The following sections provide guidance on the reporting procedures for LCA studies.

8.2.1 Summary

The LCA report can start with a summary section aimed at informing the intended target audience of the study in a very brief manner. The following information can be provided in this section: brief background and motivation of the study, the LCA approach followed, main conclusions, recommendations, and limitations. Summary section is optional as it is not mandated by ISO 14044 (2006a) and EN15084 (CEN 2013).

8.2.2 Introduction

The introduction section of the report contains a brief background describing the motivation for the LCA study and administrative information such as the following:

- An introduction to the product or services studied and its environmental significance leading to the motivation of the LCA study.
- An introduction of the project context and study goals.
- Other introductory information deemed significant and relevant to the study conducted.
- Disclaimers to avoid inappropriate use of the data and other report elements and misinterpretations.

The following is an example of such a disclaimer:

"The results presented in this study are unique to the assumptions, construction practices, traffic conditions, and design specifications for asphalt overlays constructed in North America by the Agency John Smith. When LCA is conducted for similar pavement types, geographical, technological and institutional practice differences may produce incomparable results."

Both the summary (8.2.1) and the introduction (8.2.2) are written for non-LCA experts and are followed by content described in the sections 8.2.3, 8.2.4 and 8.2.5 depending on the type of LCA following the options from figure 8-1.

8.2.3 Basic Requirements and Considerations

The basic LCA report should provide results and conclusions of the LCA in a complete and accurate manner without any bias to the intended audience. The results, data, methods, assumptions and limitations should be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. The report should also allow the results and interpretation to be used in a manner consistent with the goals of the study. Some of the elements of the interpretation phase can be used for graphical and tabular presentation of the LCI and LCIA results. Although it is not mandatory, the LCA report format targeting third-party audiences or EPD declarations, which will be introduced next, can be followed in preparation of the report. General requirements and considerations apply to LCA reports that are prepared for internal documentation and will not be shared with public, scholarly articles, etc.

It is recommended that the final project report includes the sections listed in figure 8-2:

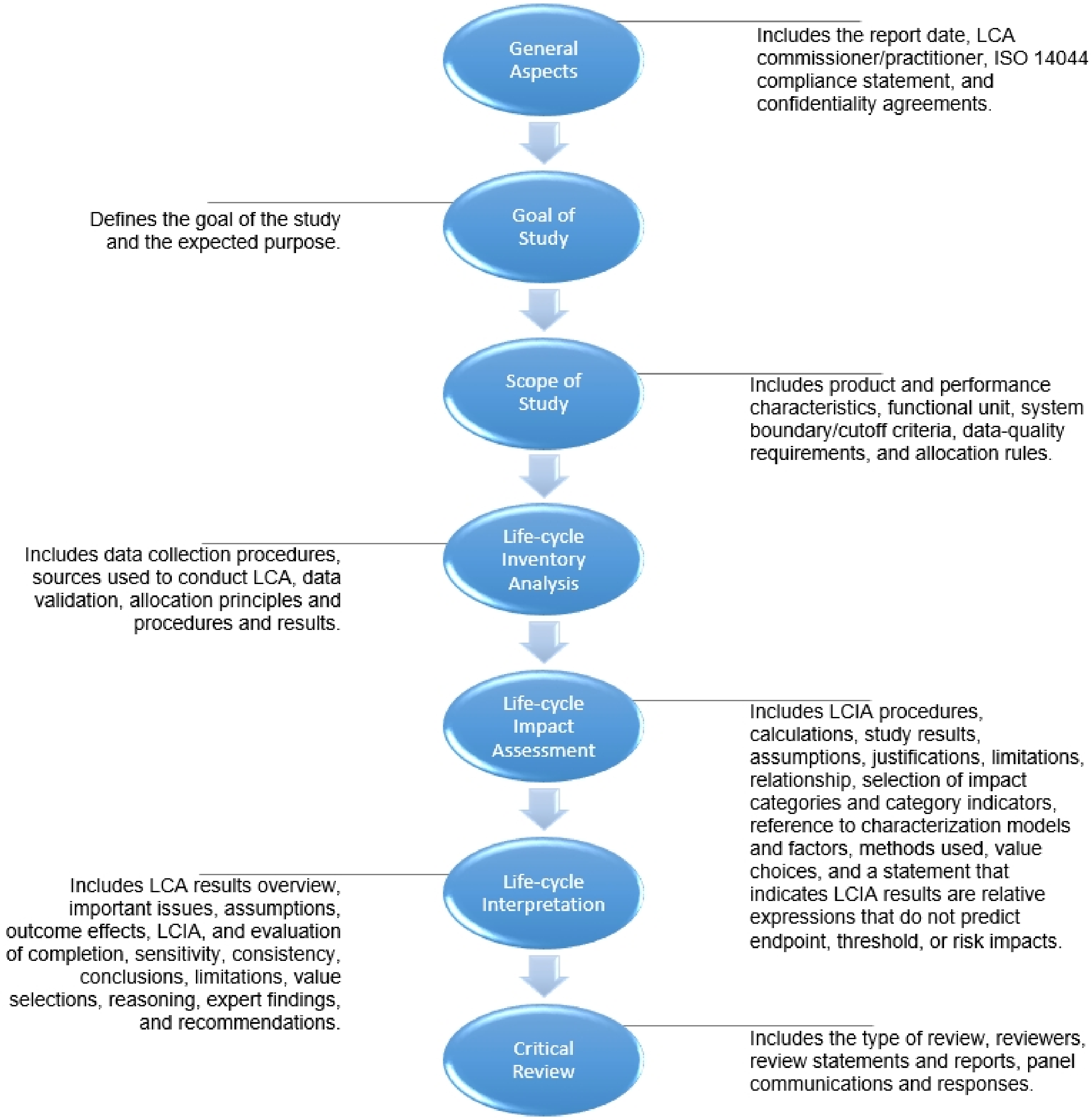

Figure 8-2. Basic LCA report aspects (Based on ISO 2006a).

8.2.4 Additional Reporting Requirements for Third-party Reports

When results of the LCA are to be communicated to any third party (i.e., interested party other than the commissioner or the practitioner of the study), regardless of the form of communication, a third-party report should be prepared. The third-party report can be based on study documentation that contains confidential information that may not be included in the third-party report. The third-party report constitutes a reference document, and shall be made available to any third party to whom the communication is made.

In addition to the reporting elements introduced in Section 8.2.3, the LCA reports for third-party audiences (e.g., interested party other than the commissioner or the practitioner of the study) should follow a specific format defined in the scoping phase (ISO 14044 [2006a]).

The final report should be organized to follow ISO 14044 requirements as shown in figure 8-3. It is recommended to use this outline as part of the project report for pavement LCA applications prepared for a third party. Additional requirements should be added if the third-party report contains comparative assertions or is for the background report for EPDs.

Comparative Assertions

According to ISO 14044 (ISO 2006a), reporting of additional data and results are required for the LCA studies to be shared with third parties; especially if it is used in supporting comparative assertions to be disclosed to the public.

In a comparative study, the equivalence of the systems being compared should be evaluated before interpreting the results. Consequently, the scope of the study should be defined in such a way that the systems can be compared. Systems should be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs and outputs, and impact assessment. Any differences between systems regarding these parameters shall be identified and reported. If the study is intended for a comparative assertion to be publicly disclosed, interested parties shall conduct this evaluation as a critical review. Impact assessment has to be part of the project report prepared for comparative assertions and intended to be disclosed to the public.

The reporting requirements include the following elements when applicable (ISO 2006a):

- Analysis of material and energy flows to justify their inclusion or exclusion.
- Assessment of the precision, completeness and representativeness of data used.
- Description of the equivalence of the systems.
- Description of the critical review process.
- Evaluation of the completeness of the LCIA.
- A statement as on international acceptance for the selected category indicators and a justification for their use.
- An explanation for the scientific and technical validity and environmental relevance of the category indicators used in the study.
- Results of the uncertainty and sensitivity analyses.
- Evaluation of the significance of the differences found.

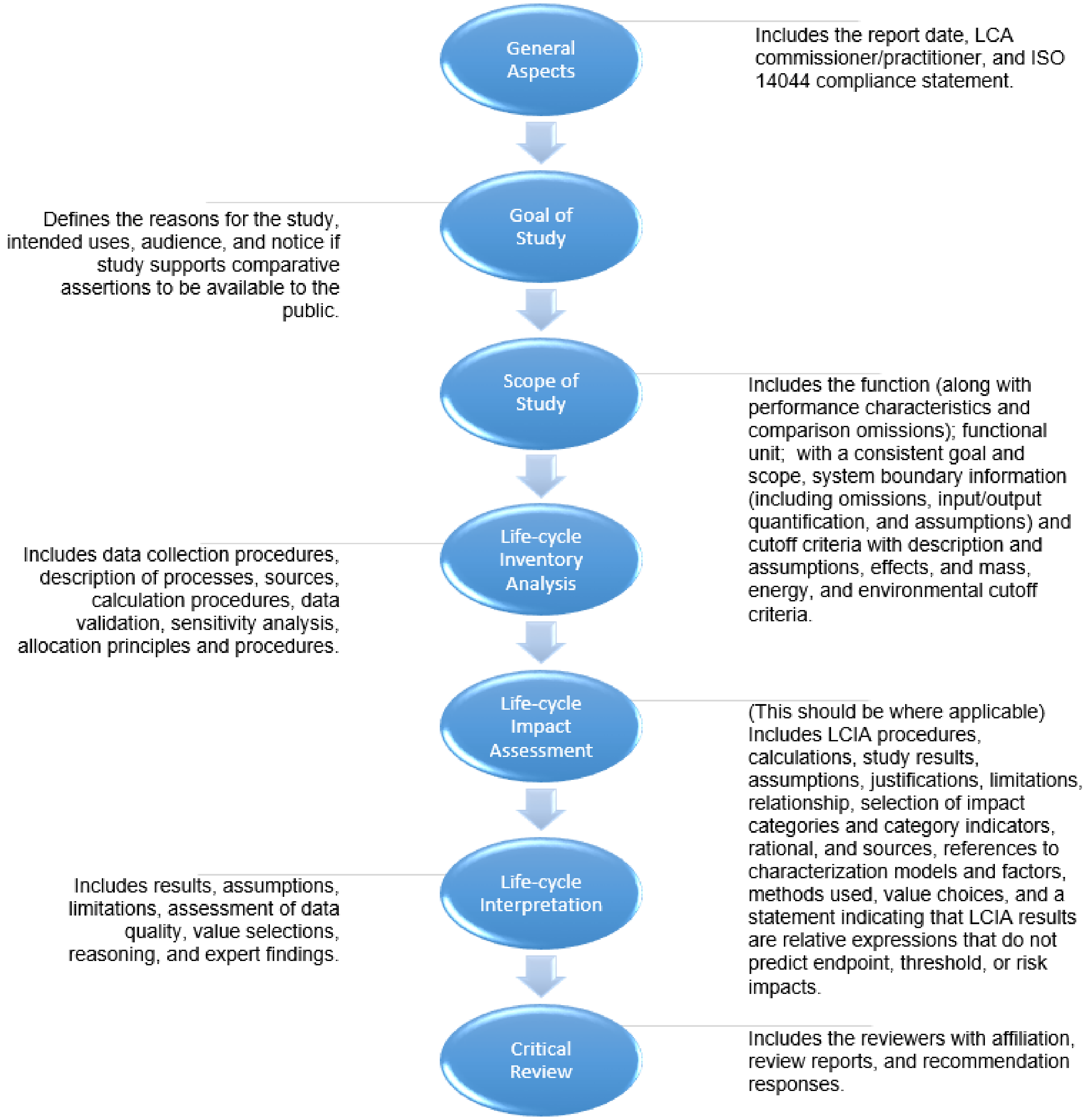

Figure 8-3. Third-party report aspects (Based on ISO 2006a).

If grouping is included in the LCA, the following shall be added:

- Procedures and results used for grouping.
- A statement that conclusions and recommendations derived from grouping is based on value choices.
- A justification of the criteria used for normalization and grouping (these can be personal, organizational or national value choices).
- The statement that "ISO 14044 does not specify any specific methodology or support the underlying value choices used to group the impact categories."
- The statement that "The value choices and judgements within the grouping procedures are the sole responsibilities of the commissioner of the study (e.g., government, community, organization, etc.)."

Background Reports for EPDs

PCRs can include additional reporting requirements for both the LCA report and the EPD derived from it. The project report is the systematic and comprehensive summary of the project documentation supporting the verification of an EPD. Additional EPD-related requirements may include the following:

- Specified laboratory results or measurements for the content declaration, functional or technical performance, and input-output flows.
- Predetermined, environmental and health information that is not covered by LCA for a product, construction process and construction service.
- Documentation of technological, geographical and time-related representativeness for generic data.

For LCA studies supporting EPDs, the following issues shall also be addressed by the report in addition to those identified above as defined by the EN15804 using the general outline shown in figure 8-4.

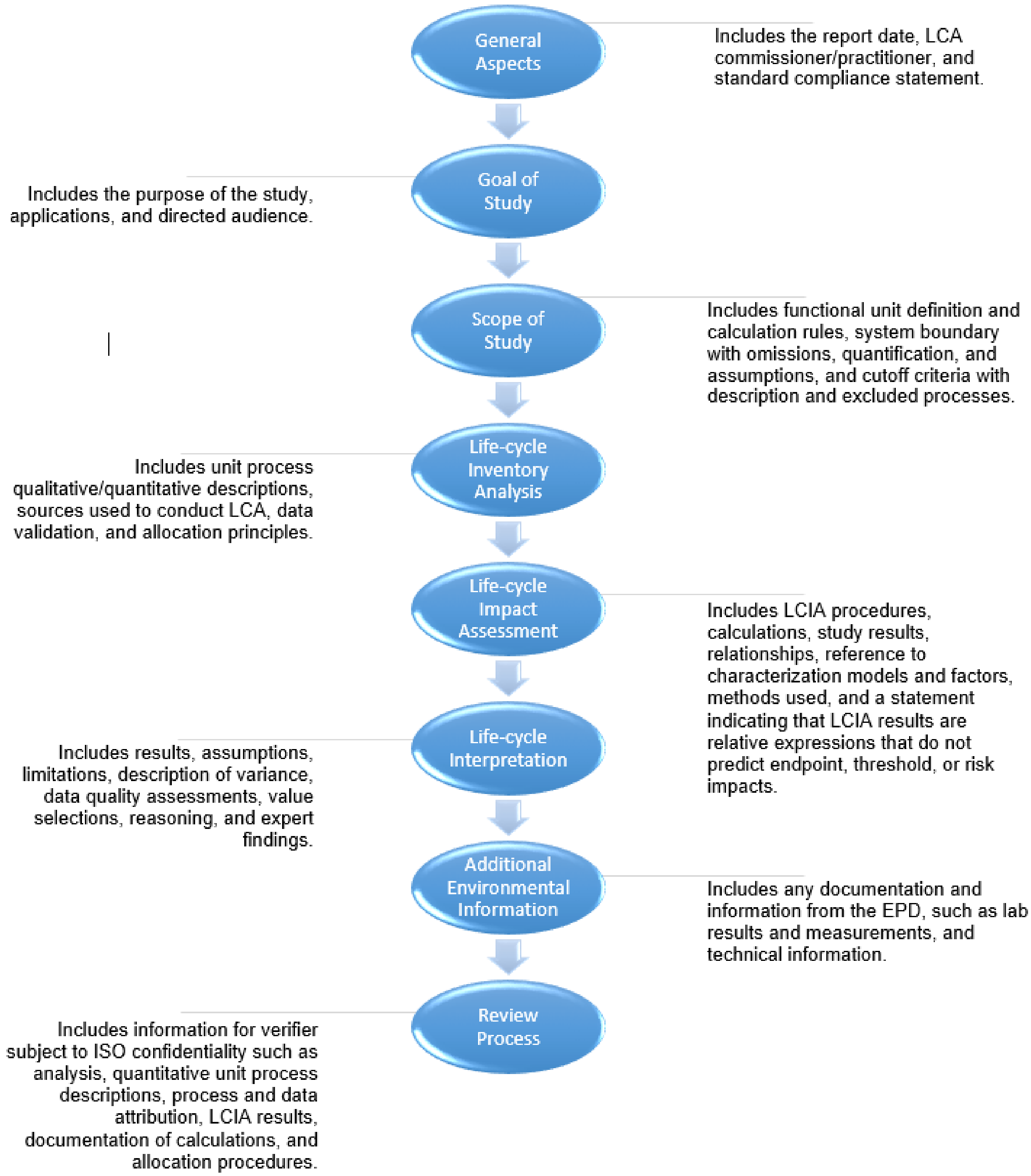

Figure 8-4. Third-party report aspects for LCA studies supporting EPDs (Based on ISO 2006a).

8.3 References

CEN. 2013. *Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products.* CEN/TC350. EN 15804 + A1. European Committee for Standardization. European Union, Brussels.

International Organization for Standardization (ISO). 2006a. *Environmental Management - Life Cycle Assessment - Requirements and Guidelines*. ISO 14044. International Organization for Standardization, Geneva, Switzerland.

APPENDIX A. PAVEMENT LCA CHECKLIST

1 Goal and Scope Definition

1.1 Goal Definition

Study level (Choose one):	☐ Network level ☐ Project level
LCA type (Choose one):	☐ Single stand-alone LCA ☐ Comparative LCA

If "Comparative LCA" is selected, state the components that are assumed to be the same across systems:

1.2 Functional Unit

1.2.1 Physical dimension

Lane length:	______km	Suggested: Max 100 km; Min 0.5 km
Lane width:	______m	
Number of lanes:		
Including shoulder:	☐	
If lane length, width, and number are not applicable, use total area:	______m^2	Such as parking lots, airports, or intersections.

1.2.2 Performance requirements

Functional design life:	_____years	
Truck traffic (AADT):		
Climate:		
Subgrade type:		
Criteria for functional performance:	_______,	_______,

1.3 Analysis Period

Method used to determine analysis period:	Analysis period: _____years

1.4 Life Cycle Inventory

1.4.1 Primary energy:	☐		
Clearly distinguish between feedstock energy and combusted energy:	☐		
1.4.2 Greenhouse gases	☐		
CO_2:	☐	CH_4:	☐
N_2O:	☐	Other:	
1.4.3 Material flows	☐		
1.4.4 Air pollutants			
O_3:	☐	PM_{10}:	☐
$PM_{2.5}$:	☐	SO_2:	☐
CO:	☐	Lead:	☐
Volatile organic compounds:	☐	NO_X:	☐
Others:	________,	________,	
1.4.5 Water pollutants	☐		
1.4.6 Solid waste flows	☐		
1.4.7 Other inventory categories	________,	________,	

1.5 Pavement Structure Design and Life Cycle Phases

1.5.1 Pavement structure design (for each system)			
Surface:	☐	Shoulder:	☐
Base or subbase:	☐	Drainage:	☐
Subgrade:	☐	Roadway lighting:	☐
1.5.2 Material Production Phase			
Raw material #1 [List each of them]:			
Material production:	☐		
Feedstock energy:	☐		
Transport of materials to site:	☐		
1.5.2.1 *Engineered material*			
Mixing in plant (HMA or PCC):	☐		

1.5.3 Construction Phase and Maintenance and Rehabilitation Phase			
Transport of materials to site:	☐		
Transport from/to plant:	☐		
Transport of recycled material:	☐		
Equipment usage:	☐		
Water use:	☐		
Work zone traffic congestion:	☐		
Vehicle technology change:	☐		
Traffic growth:	☐		
Lighting energy, if at night:	☐		
Movement of equipment:	☐		
Temporary infrastructure:	☐		
Equipment manufacturing:	☐		
Factory or plant construction:	☐		
1.5.4 Use Phase			
1.5.4.1 *Vehicle operation*			
Impact to fuel economy from roughness:	☐	Damage to freight:	☐
Damage to vehicle:	☐	Vehicle tire wear:	☐
Traffic growth:	☐		
Change in vehicle technology:	☐		
1.5.4.2 *Heat island*	☐		
1.5.4.3 *Non-GHG climate change mechanism*	☐		
1.5.4.4 *Water pollution from runoff*	☐		
1.5.4.5 *Roadway lighting*	☐		
1.5.4.6 *Carbonation*	☐		
1.5.5 End-of-Life Phase			
1.5.5.1 *Recycling*	☐		
Allocation:	☐		
1.5.5.2 *Landfill*			
Hauling of materials:	☐		
Long-term water pollution:	☐		
1.6 Impact Assessment			
1.6.1 Global Warming			
Global warming potential (GWP):	☐		
Source :	☐ IPCC TAR ☐ IPCC AR4 ☐ Other	Time horizon (e.g. 100-yr, 20-year, etc.):	
1.6.2 Other impact categories (List one by one.)			
Impact category indicator:			
Source for calculation:			

1.7 Sensitivity Analysis

1.7.1 Variables

Variables that are used to perform sensitivity analysis:	________, ________, ________, ________, ________,

2 Models and Data Sources

2.1 Material Production

2.1.1 Material LCI (List all the LCI sources)		
LCI source #[1,2,…,n] name:		
Type:	☐ LCI Tool (refers to database from company or research organizations) ☐ LCI Study (refers to publish journal paper or study report)	
Meet ISO standard?	☐	
Data quality evaluation:	☐	
Statistical analysis:	☐	

2.2 Construction

2.2.1 Maintenance and rehabilitation schedule		
Determined from:		
2.2.2 Equipment use	☐	
Construction schedule analysis:	☐	Data source: Model:
Equipment emission:	☐	Data source: Model:
Equipment fuel use:	☐	Data source: Model:
Truck emission:	☐	Data source: Model:
Truck fuel use:	☐	Data source: Model:
2.2.3 Construction-related traffic	☐	
Work zone traffic analysis:	☐	Data source: Model:
Traffic network analysis:	☐	Data source: Model:
Additional emission:	☐	Data source: Model:
Additional fuel use:	☐	Data source: Model:

2.3 Use		
2.3.1 Vehicle operation	☐	
Pavement performance model:		Data source:
2.3.1.1 Impact to fuel economy	☐	
Pavement – fuel use model:		Data source:
2.3.1.2 Damage to vehicle	☐	
Pavement – vehicle model:		Data source:
2.3.1.3 Damage to freight	☐	
Pavement – freight model:		Data source:
2.3.1.4 Vehicle tire wear	☐	
Pavement – tire model:		Data source:
2.3.2 Urban heat island		
2.3.2.1 Albedo effect	☐	
Pavement aging – albedo model:		Data source:
Albedo – heat island model:		Data source:
Heat island – energy consumption relationship:		Data source:
2.3.2.2 Evaporative cooling	☐	
Evaporation – heat island relationship:		Data source:
Heat island – energy consumption relationship:		Data source:
2.3.3 Non-GHG climate change effects		
2.3.3.1 Albedo – radiative forcing	☐	
Albedo – radiative forcing model:		Data source:
Radiative forcing – GWP relationship:		Data source:
2.3.4 Leachate	☐	
Pollutant transport model:		Data source:
2.3.5 Carbonation	☐	
Carbonation model:		Data source:
2.3.6 Roadway lighting	☐	
Electricity use model:		Data source:
2.4 End-of-Life		
2.4.1 Recycling	☐	
Method used to allocate input and output:		
2.4.2 Landfill	☐	
2.4.2.1 *Truck use*		
Truck emission:	☐	Data source: Model:
Truck fuel use:	☐	Data source: Model:

APPENDIX B. GLOSSARY

Terminology	Definition	Source
Admixture	A material other than water, aggregates, and portland cement (including air-entraining portland cement, and portland blast furnace slag cement) that is used as an ingredient of concrete and is added to the batch before and during the mixing operation.	Taylor et al. 2006
Aggregate	Granular material, such as sand, gravel, or crushed stone used with a hydraulic cementing medium to produce either concrete or mortar; or used with asphalt cement to produce asphalt concrete; or used in the base and/or subbase layers of a pavement structure.	Taylor et al. 2006
Allocation	Dividing the input or output flows between the process or a product system being studied and other product systems	Based on ISO 2006c
Analysis Period	The time period used in the LCA model to capture the influence of current and anticipated future decisions in the pavement life cycle that covers the expected service life under a particular set of use conditions which may form the basis of estimating the service life under other in-use conditions.	N/A
Ancillary input	Input material used by the unit process that does not make up a part of the end product	Based on ISO 2006c
Attributional LCA	LCA that is used for reporting purposes looking at product, company, regional or national levels, focusing on the environmental impacts caused by a product or application using average known (and usually) historic consumption data	N/A
Average data	Data representative of a product, product group or construction service, provided by more than one supplier	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Background data	Data in processes not under the direct control of the LCA owner	N/A
Biomass	Material of biological origin, excluding material embedded in geological formations or transformed to fossil	CEN/TR 14980:2004 © CEN, reproduced with permission
Carbonation	Reaction between carbon dioxide and the products of portland cement hydration to produce calcium carbonate	Taylor et al. 2006
Category endpoint	A characteristic or facet of natural environment, human health, or resources that identifies an environmental issue or concern	Based on ISO 2006b
Characterization factor	A factor obtained from a characterization model used to convert an assigned life-cycle inventory analysis result to the category indicator common unit	Based on ISO 2006c
Comparative assertion	An environmental claim to superiority or equivalence of one product versus a competing product that is functionally equivalent	Based on ISO 2006c
Completeness check	Verifying sufficiency of information from the life-cycle assessment phases to draw conclusions that align with the goal and scope definition	Based on ISO 2006b
Consequential LCA	LCA that is used for decision support looking at regional or national levels, and focuses on the environmental impacts induced by decisions	N/A

Terminology	Definition	Source
Consistency check	Verifying the consistent application of assumptions, methods and data and the alignment with the goal and scope definition are performed before the conclusions are drawn	Based on ISO 2006b
Construction element	Part of a construction containing a defined combination of products	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Construction product	Item manufactured or processed for incorporation in construction works	EN 15643-1:2010 © CEN, reproduced with permission
Construction service	Activity that supports the construction process or subsequent maintenance	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Co-product	Any of two or more marketable materials, products or fuels from the same unit process, but which is not the object of the assessment. NOTE Co-product, by-product and product have the same status and are used for identification of several distinguished flows of products from the same unit process. From co-product, by-product and product, waste is the only output to be distinguished as a non-product	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Critical review	A review to ensure consistency between a life cycle assessment and International LCA Standard principles and requirements	Based on ISO 2006b
Cut-off criteria	Documentation of study exclusions such as the amount of material or energy flow or the level of environmental significance associated with unit processes	Based on ISO 2006b
Data quality	Data characteristics that indicate their ability to satisfy requirements	Based on ISO 2006b
Declared unit	Construction product quantity used as an EPD reference unit (based on information modules)	Based on ISO 2007
Direct land use change	A change in the assessed product systems use or management of land	Based on ISO 2013
Elementary flow	Inputs to the system that are direct from the environment with no human alteration, or outputs from the system discharged to the environment without subsequent human alterations	Based on ISO 2006b
End-point indicator	Environmental indicator based on a damage-based approach close to areas of protection or recognizable value to society organized in damage to the natural environment, human health, natural resources or the man-made environment	N/A
Energy flow	Inputs or outputs in processes or systems, measured in energy units	Based on ISO 2006b
Environmental aspect	The element of activity, product, or service that impacts the environment	Based on ISO 2006c
Environmental mechanism	Impact category physical, chemical and biological processes that link life-cycle inventory analysis to category indicators and endpoints	Based on ISO 2006b
Environmental performance	Performance associated with environmental aspects	Based on ISO 2010

Terminology	Definition	Source
Environmental product declaration (EPD)	Standardized declaration that quantifies the environmental impact of a product using a life-cycle assessment according to ISO standards	Based on ISO 2007
Estimated Service Life	Service life that a building or an assembled system (part of works) would be expected to have in a set of specific in-use conditions, determined from reference service life data after taking into account any differences from the reference in use conditions	EN 15978:2011 © CEN, reproduced with permission
Evaluation	Life-cycle interpretation phase component that supports life-cycle assessment results	Based on ISO 2006b
Feedstock energy	Nonfuel energy use; the energy used as a raw material for purposes other than for heat, power, and electricity generation	US Energy Information Administration
Foreground Data	Data in processes under the direct control of the EPD owner	Earthsure 2011
Functional equivalent	A comparison basis that uses different objects or systems, but performs the same function based on quantified functional or technical requirements	Based on ISO 2010
Functional unit	Product system measurement of performance to provide a reference unit	Based on ISO 2006b
Gravity analysis	An analysis that statistically identifies the greatest contributing data to the indicator result.	Based on ISO 2006c
High heating value	The lower heating value with the addition of the heat of vaporization of the water content in the fuel	N/A
Impact Assessment	An assessment that shows the environmental impacts of life-cycle inventory results on a product system	Based on ISO 2006c
Impact category	A category showing an environmental issue to which assignments of life-cycle inventory analysis may be made	Based on ISO 2006b
Impact category indicator	The measurable depiction of an impact category	Based on ISO 2006b
Indicator	A quantifiable representation of an impact category	N/A
Information module	Collection of data used as a Type III environmental declaration basis that covers product life cycle unit processes	Based on ISO 2006a
Input	Product, material or energy that is put into a process or system	Based on ISO 2006b
Interested party	Those concerned with or affected by a product or system's environmental performance, or life-cycle assessment results	Based on ISO 2006b
Intermediate flow	Product, material or energy flow among unit processes	Based on ISO 2006b
Intermediate product	An output from one unit process that is an input to other unit process	Based on ISO 2006b

Terminology	Definition	Source
Interpretation	The final phase of an LCA identifying and evaluating substantial issues derived from the life-cycle inventory and life-cycle impact assessment phases in order to reach conclusions and recommendations that align with the goal and scope	Based on ISO 2006c
Life cycle	The successive phases of a product or system, from raw material to final disposal	Based on ISO 2006b
Life cycle assessment	The compilation and evaluation of a system's inputs, outputs, and environmental impacts over the entire life cycle	Based on ISO 2006c
Life cycle impact assessment	The phase of an LCA that shows the extent and significance of a system's environmental impacts for the entire life cycle	Based on ISO 2006b
Life cycle interpretation	The phase of an LCA where inventory analysis and impact assessment results are compared to the defined goal and scope in order to obtain conclusions and recommendations	Based on ISO 2006c
Life cycle inventory	The phase of an LCA that compiles and quantifies product inputs and outputs for the entire life cycle	Based on ISO 2006b
Life cycle inventory analysis	The result of the life cycle inventory analyses	N/A
Low heating value	A property of a fuel, defined as the amount of heat released by combusting a specified quantity	N/A
Mid-point indicator	Environmental indicator based on a problem-based approach related to human environmental interventions, either physical, chemical or biological, in particular resources extraction, emissions and land use.	N/A
Module	Collection of data used as a Type III environmental declaration foundation that covers product life cycle unit processes	Based on ISO 2007
Non-renewable energy	Energy from sources which are not defined as renewable energy sources	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Non-renewable resource	Resource with a set quantity that is irreplaceable in a human timescale	Based on ISO 2010
Output	Product, material or energy that exits a process	Based on ISO 2006c
Performance	Expression relating to the magnitude of a particular aspect of the object of consideration relative to specified requirements, objectives or targets	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Primary data	Raw data collected by the individuals in question, e.g., electricity invoices, stack test results, monthly monitoring data, etc.	Earthsure 2011
Process	A series of related actions or steps taking inputs into outputs	Based on ISO 2006b
Process energy	The energy input required to operate unit process equipment or underlying processes, not including production energy inputs and the actual energy delivery	Based on ISO 2006b
Product	A manufactured or refined goods or substance	Based on ISO 2006b
Product category	A set of products that can achieve equivalent roles	Based on ISO 2006a

Terminology	Definition	Source
Product category rules	A set of defined rules, requirements and guidelines used to develop Type III environmental declarations for product categories	Based on ISO 2006a
Product system	A collection of unit processes with product flows that perform defined functions and model the product life cycle	Based on ISO 2006b
Program operator	Individual that conducts a Type III environmental declaration program	Based on ISO 2006a
Range	Either the 'highest probable' and 'lowest probable' when determined data provided by EPD program operator or the 10th and 90th percentile determined using statistical analysis	CLF 2013
Raw material	Primary material used to produce a product	Based on ISO 2006b
Reference flow	Product system output process measurements required to fulfil the function indicated by the functional unit	Based on ISO 2006b
Reference service life	The construction product service life known to be expected under a particular set of in-use conditions and which may aid in estimating the service life for other in-use conditions	Based on ISO 2007
Reference service life data	Information that includes the reference service life and any qualitative or quantitative data describing the validity of the reference service life	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Releases	Air emissions and water and soil discharges	Based on ISO 2006b
Renewable energy	Energy from renewable non-fossil sources	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Renewable resource	A resource that is replaced naturally on a human time scale	Based on ISO 2010
Reporting	A detailed, organized, and complete documentation of the results, data, methods, assumptions, and limitations aligned with the goal of the study clearly stating the complexities and trade-offs of the LCA in a comprehensible form	Based on ISO 2006c
Scenario	Collection of assumptions and information concerning an expected sequence of possible future events	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Secondary Data	Aggregated or modified data from a reputable source, e.g., descriptions of the local electric grid derived from the local utility, published peer reviewed articles, etc.	Earthsure 2011
Secondary fuel	Fuel recovered from previous use or from waste which substitutes primary fuels	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Secondary material	Material recovered from previous use or from waste which substitutes primary materials	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Sensitivity analysis	A systematic process for estimating the impacts on the study outcome from choices made regarding methods and data	Based on ISO 2006b
Sensitivity check	Verifying that the sensitivity analysis information is relevant for drawing conclusions and making recommendations	Based on ISO 2006b
Specific data	Data representative of a product, product group or construction service, provided by one supplier	EN 15804:2012+A1:2013 © CEN, reproduced with permission
System boundary	A set of criteria that indicates unit processes associated with a part of a product system	Based on ISO 2006b

Terminology	Definition	Source
Tertiary data	Data aggregated from many sources, e.g., in commercial LCI databases.	Earthsure 2011
Third party	Individual or group independent of the involved parties	Based on ISO 1999
Transparency	Open, complete, and comprehensible access to information	Based on ISO 2006b
Type III environmental declaration	An environmental declaration offering quantified environmental data from fixed parameters and additional environmental information	Based on ISO 2006a
Uncertainty	Uncertainty is a measure of the quality of LCA data. Uncertainty should be evaluated as a part of the LCA prepared to create an EPD based on this PCR.	CLF 2013
Uncertainty analysis	A systematic process to quantify the uncertainty from life-cycle inventory analysis results due to the combined effects of model imprecision, input uncertainty and data variability	Based on ISO 2006b
Unit process	The smallest component of the life-cycle inventory analysis with quantification of input and output data	Based on ISO 2006b
Upstream/Down stream process	Process(s) that either precedes (upstream) or follows (downstream) a given life cycle stage	EN 15804:2012+A1:2013 © CEN, reproduced with permission
Variability	In this document variability refers to fluctuations in data due to process and material differences such as different manufacturing plants, crushed vs. natural aggregate or different transportation distances	CLF 2013
Waste	Substance or object which the holder discards or intends or is required to discard	EN 15804:2012+A1:2013 © CEN, reproduced with permission

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APPENDIX C. SUGGESTED READING

Most of the studies reviewed for the development of this framework have an emphasis on project-level decision making that requires detailed information input by the user and the use of special databases, although several others are intended more for network-level decision making that requires access and use of pavement management system data. This appendix presents a list of suggested reading sources relevant to practical implementation of LCA principles.

Many of these studies focus on addressing several specific questions, after an initial goal of establishing the framework and data sets. These include specific questions regarding selection and design of earthwork, pavement materials, construction approaches and preservation treatment timing. Each study proposes a framework for addressing the specific questions, some more broadly to address an extensive range of questions whereas others have a narrower focus to address a smaller set of questions. One paper sets out a very broad framework with the intention of setting a standard for all pavement LCA (Kendall and Santero 2010). In general, the goals found in the review of the LCA studies can be categorized as follows:

- *Develop a generic framework for new pavement materials, design, construction, and preservation*. These studies set out to develop a generic framework for pavement LCA, or a subset of LCA investigations. Examples include studies by Yu and Lu (2012); Hendrickson et al. (1997); Weiland and Muench (2010); Giudice, La Rosa, and Risitano (2005); Huang, Bird, and Heidrich (2009); Rajendran and Gambatese (2007); Wang et al. (2012a); Harvey et al. (2010); and Santero, Harvey, and Horvath (2011).
- *Compare the environmental impact of new and rehabilitated pavements*. These studies compare different material types and structures, often focused on concrete versus asphalt pavements, or comparing alternative design and materials options. Some examples include Zapata and Gambatese (2005); Rajendran and Gambatese (2007); Santero and Horvath (2009); Milachowskl, Stengel, and Gehlen (2011); and Ram et al. (2011). An additional document by Santero, Harvey, and Horvath (2011) focuses on a comparison of design lives.
- *Assess environmental impacts of recycling*. These studies are using LCA to assess the environmental impact of recycling, including the use of supplementary cementitious materials (SCMs), recycled ground tire rubber (GTR), and reclaimed asphalt pavement (RAP). Example studies include Bartolozzi et al. (2011); Santero, Harvey, and Horvath (2011); Fiksel et al. (2009); and Ventura, Moneron, and Jullien (2008).
- *Approach for including LCA in decision-making processes*. These studies look at how LCA can be used in various decision-making processes, and include work by Athena (2006); Chan and Tighe (2012); Mukherjee and Cass (2011); Kucukvar et al. (2014); Mack et al. (2012); and Wang et al. (2012b).
- *Consideration of cost and environmental impact*. These studies all discuss combining environmental impacts from LCA with cost considerations from LCCA, and include work by Zhang et al. (2010); Gosse and Clarens (2012); and Wang et al. (2012b); sometimes indicators of social impacts are included, such as in the study by Heijungs, Huppes, and Guinee (2010).
- *Compare impact assessment methodologies*. These studies compare differences in indicators for different decisions, examples include Huang, Spray, and Parry (2013); Gosse and Clarens (2012); Dreyer, Niemann, and Hauschild (2003); Ventura, Moneron,

and Jullien (2008); and Kucukvar et al. (2014), the latter of which ranks how "influential" different indicators are based on expert opinion.

- *Compare LCA approaches in Europe*. Carison (2011) compares LCA approaches in Europe and found that the approach followed should change depending on the questions to be answered, the system boundaries, and the functional unit.
- *Effects of road maintenance for different types of vehicle propulsion in the fleet*. These studies look at the timing and effects of maintenance on the life cycle, most of them also looking at considering effects of materials production and construction versus the use phase. Examples include Chiu, Hsu, and Yang (2008); Wang et al. (2012a); Yu, Lu, and Xu (2013); Mukherjee and Cass (2011); and NTUA (2006).
- *Understand uncertainty from data variability*. Approaches for considering uncertainty in data are considered in Athena (2006); Chappat and Bilal (2003); and Milachowskl, Stengel, and Gehlen (2011). For example, Athena (2006) looks at the sensitivity of changes in pavement type and considers whether the differences are significant.

There are a number of available source documents that provide good examples of the various reporting elements. Suggested documents categorized by topical report area are listed below:

- *Reporting of goal and scope elements.* These studies report their goal and scope elements clearly and comprehensively; examples include documents by Weiland and Muench (2010), Huang, Bird, and Heidrich (2009), and Wang et al. (2012a).
- *Reporting of data quality assessment results.* These studies report their data quality assessment results qualitatively or quantitatively; examples include reports by Weiland and Muench (2010) and by Skone and Gerdes (2008). In addition, the following studies report uncertainty analysis results: Gschösser, Wallbaum, and Boesch (2012) and Noshadravan et al. (2013).
- *Reporting of sensitivity analysis results.* These studies present sensitivity analysis of methodology choices in pavement LCA; examples include reports by Huang, Spray, and Parry (2013), Loijos, Santero, and Ochsendorf (2013), Chen et al. (2010), and Sayagh et al. (2010).
- *Reporting of final LCA results.* These studies report the LCA results clearly and visually; examples include reports by Santero and Horvath (2009), Wang et al. (2012a), Al-Qadi et al. (2015), and Ram et al. (2011).

EPDs, in general, are good examples of LCA reporting since they follow ISO and PCR reporting requirements. Some of the examples of EPDs open to public include those by Bushi, Finlayson, and Meil (2014), Athena (2014), and Acciona (2013).

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