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Life-Cycle Assessment of Airfield Pavements and Other Airside Features: Framework, Guidelines, and Case Studies

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Final Report

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16. Abstract

The guidelines for the conduct of life-cycle assessment (LCA) studies for airfields include recommendations for all phases of LCA, including goal and scope definition, life-cycle inventory development, impact assessment, interpretation and critical review, and reporting. Four example case studies are presented that were prepared with participation and data from recently completed projects from four U.S. airports, although the scope is limited to airside civil infrastructure. The case studies are intended to demonstrate the framework and to provide examples as to how the airfield LCA guidelines can be used to quantify the environmental impacts of different kinds of decisions made by airports. The guidelines are expected to be updated as experience is gained with LCA studies for airfields.

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A.A. Butt, J.T. Harvey, D. Reger, A. Saboori, M. Ostovar, and M. Bejarano	A.A. Butt, J.T. Harvey, A. Saboori, D. Reger, M. Ostovar, and M. Bejarano	Technical Report Documentation Page, Item 7: Author(s)
, and John Kulikowski of the U.S. Air Force for reviewing the airfield life-cycle assessment (LCA) guidelines.	, John Kulikowski of the U.S. Air Force for reviewing the airfield life-cycle assessment (LCA) guidelines, and Joseph Shacat (Director of Sustainable Pavements) of the National Asphalt Pavement Association for reviewing the final report.	Acknowledgements, page iii/iv.
for data sharing.	for sharing data.	Acknowledgements, page iii/iv.
Figure 23	Replaced figure 23 in its entirety.	Section 8.3.2, page 116.
Figure 23. Cross-Section Thicknesses of Different Layers of Erosion and Shoulder Pavements	Figure 23. Cross-Section Thicknesses of the Erosion and Shoulder Pavements' Different Layers	Figure caption, figure 23, page 116.
Table 23	Replaced table 23 in its entirety.	Section 8.4.2, page 122.
Ground tire rubber (GTB)	Ground tire rubber (GTR)	Section 8.4.2.1, page 124; section 8.4.3, page 127.
Figure 26	Replaced figure 26 in its entirety.	Section 8.4.2.1, page 125.
Table 27	Replaced data in table 27.	Section 8.4.2.1, page 125.
Figure 28	Replaced figure 28 in its entirety.	Section 8.4.2.2, page 126.
Table 28	Replaced data in table 28.	Section 8.4.2.2, page 126.
(that is, consumed nonrenewable PED is about one-third less and emissions are about one-fifth less)	(that is, consumed nonrenewable PED is about one-third less and emissions are about one-fourth less)	Section 8.4.3, page 127.
There are two main reasons for this: WMA mixes use less virgin binder and are prepared using lower mixing temperatures.	Deleted sentence in its entirety.	Section 8.4.3, page 127.

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But while the use of inventories for substitute materials introduced some uncertainty into these results, it is still likely that the inventories were similar enough that they did not significantly change the interpretation.	Although substituting these materials' inventories introduced some uncertainty into the results, the inventory differences were unlikely to have been large enough to significantly change the interpretation.	Section 8.4.3, page 127.
The transportation of the WMA with reclaimed materials consumed a greater amount of energy than HMA because of the additional transport requirements of the reclaimed materials.	The transportation of the WMA with reclaimed materials consumed slightly more energy than transportation of the HMA because of the reclaimed materials' additional transport requirements.	Section 8.4.3, page 127.
Table 30	Replaced table in its entirety.	Section 8.5.2, page 130.
Table 34	Replaced data in table 34.	Section 8.5.2, page 133.
Figure 30	Replaced figure 30 in its entirety.	Section 8.5.4, page 134.
Figure 31	Replaced figure 31 in its entirety.	Section 8.5.4, page 134.
Figure 31. The GWP (Tonnes of CO_2-e) Comparison Between HMA and WMA	Figure 31. The GWP (kg of CO_2-e) Comparison Between HMA and WMA	Section 8.5.4, page 134.
Figure 33	Replaced figure 33 in its entirety	Section 8.5.4, page 136.
Figure 33. Selected TRACI Impacts for Three Different Scenarios	Figure 33. Selected TRACI Impacts (in tonnes) for Three Different Scenarios	Section 8.5.4, page 136.
Table 40	Replaced table 40 in its entirety.	Section 8.6.2, page 147.
Figure 36	Replaced figure 36 in its entirety.	Section 8.6.2, page 148.
Figure 37	Replaced figure 37 in its entirety.	Section 8.6.2, page 148.
Section 8.6.3.1	Replaced section 8.6.3.1 in its entirety.	Section 8.6.3.1, page 149.
Of the three asphalt alternatives (4R, 5R, and NS2), 5R had the highest environmental impacts for the TRACI indicators, while 4R had the highest consumed nonrenewable PED.	Of the three asphalt alternatives (4R, 5R, and NS2), 5R had the highest environmental impacts for the TRACI indicators (GWP and $PM_{2.5}$), while 4R had the highest consumed PED-FS (feedstock energy).	Section 8.6.3.2, page 149.
NS2 had the least impacts both in terms of energy and emissions.	NS2 had the lowest impact in terms of energy required and emissions, although not for GWP (due to the high cement content of this alternative).	Section 8.6.3.2, page 149.

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NS2 required about 2.5 times and 2 times less nonrenewable PED to be consumed than options 4R and 5R, respectively. The impacts from transportation were also small in the case of NS2. In terms of the materials stage, 4R had the least impacts but it also had high transportation impacts that more than off-set the materials stage.	The total PED determined for NS2 was 4% lower than 5R and 25% lower than 4R. As with the concrete alternatives, transportation and construction were not major contributors to any impact category other than smog formation; and in this category construction was consistently the dominant contributor, with 53% to 59% of total smog formation across all alternatives.	Section 8.6.3.2, page 149.
This also indicates that doing an LCCA and LCA together can help airports select more sustainable options and provides an opportunity to consider not only costs but also energy and a number of environment-related impacts for decision support of pavement design alternatives.	This case study shows that performing LCCA and LCA together provides opportunity for the airports to consider not only costs but also energy and a number of environment-related impacts for decision support in the selection of more sustainable pavement design alternatives.	Section 8.6.3.2, page 149.

Pages replaced: Technical Report Documentation Page, iii/iv, 116, 122, 124, 125, 127, 130, 133, 134, 136, 147, 148, and 149.

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ACRP	Airport Cooperative Research Program
ADP	Abiotic depletion potential
ASTM	American Society for Testing and Materials
BBANDAINC	Bowman, Barrett & Associates Inc.
BNA	Nashville International Airport
BOS	Boston Logan International Airport
CARB	California Air Resources Board
CEN	European Committee for Standardization
CFC	Chlorofluorocarbon
CLCA	Consequential life-cycle assessment
CO	Carbon monoxide
CO_2	Carbon dioxide
COU	Columbia Regional Airport
CTBR	Cement-treated base with reclaimed aggregate
DDM	Data driven model
DOT	Department of Transportation
EIA	U.S. Energy Information Administration
EIO-LCA	Economic Input-Output Life-Cycle Assessment
EOL	End of Life
EP	Eutrophication potential
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
GCR	Ground crumb rubber
GHG	Greenhouse gas
GTR	Ground tire rubber
GWP	Global warming potential
HMA	Hot mix asphalt
IC5	Bolingbrook’s Clow International Airport
IEA	International Energy Agency
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
J	Joule
JFK	John F. Kennedy International Airport
JMF	Job mix formula
LCA	Life-cycle assessment
LCCA	Life-cycle cost analysis
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LED	Light-emitting diode
M&R	Maintenance and rehabilitation
Massport	Massachusetts Port Authority
MJ	Megajoule

NAPA	National Asphalt Pavement Association
NOAB	New Orleans Aviation Board
NO_x	Oxides of nitrogen
NRMCA	National Ready Mixed Concrete Association
O_3	Ozone
ODP	Ozone depletion potential
ORD	Chicago O’Hare International Airport
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PANYNJ	Port Authority of New York and New Jersey
PCA	Portland Cement Association
PCC	Portland cement concrete
PCR	Product Category Rule
PED	Primary energy demand
PED-FS	PED from energy sources (feedstock), both renewable and nonrenewable, not consumed as energy
PED-NR	PED from nonrenewable sources consumed as energy
PED-R	PED from renewable sources consumed as energy
PM	Particulate matter
PM_{10}	Particulate matter 10 micrometers or less in diameter
$PM_{2.5}$	Particulate matter 2.5 micrometers or less in diameter
POCP	Photochemical ozone creation potentials
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingles
SBR	Styrene-butadiene rubber
SBS	Styrene-butadiene styrene
SCM	Supplementary cementitious material
SO_2	Sulfur dioxide
TJ	Terajoule
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UC	University of California
UCPRC	University of California Pavement Research Center
U.S.	United States
USLCI	United States Life Cycle Inventory
UV	Ultraviolet
WMA	Warm mix asphalt

EXECUTIVE SUMMARY

For many years, the Federal Aviation Administration (FAA) has taken measures to improve safety, enhance efficiency, reduce cost and improve United States (U.S.) airfield infrastructure sustainability. To quantify and reduce the economic cost of expanding and preserving airfield systems, the FAA has used life-cycle cost analysis (LCCA). However, efforts to address sustainability are incomplete if environmental impacts due to airfield infrastructure are not considered. Life-cycle assessment (LCA) is an approach that can identify and quantify the life-cycle environmental impacts of a system such as the airfield infrastructure. Currently, FAA decisions regarding airfield infrastructure do not require using the LCA approach for evaluating airfield infrastructure. However, some airports have created or are interested in creating their own sustainability improvement plans either as a part of airport long-range planning (Sustainability Master Plans) or as a stand-alone process (Sustainable Management Plans). Prior to this project, some airfield infrastructure case studies were completed, but a comprehensive framework has yet to be thoroughly developed.

The primary objective of this project was to develop an LCA framework that will support the FAA and airports' capacity and capability to consider environmental impacts in decision-making. The framework is envisioned to function as the first version of a living document that will be updated as experience is gained from case studies and from other development and implementation efforts. An airfield LCA framework and guidelines have been developed as part of this project. The guidelines include recommendations for all phases of LCA, including goal and scope definition, life-cycle inventory development, impact assessment, interpretation, critical review, and reporting. The framework is intended for LCA studies that support decisions regarding the life cycles of air-side features found inside the fence line of an airfield, including airside pavements (such as runways, overruns, taxiways, aprons, shoulders, and airside land vehicle roads), drainage, airfield lighting and other lighting and navigational aids, exterior fencing, and maintenance of airside grounds. Landside and airside features related to aircraft servicing and fueling, fire suppression systems, wash racks and other cleaning equipment, gate operations, and all buildings have not been included in the study's scope.

The LCA guidelines and airfield LCA framework developed for the FAA, as well as four case studies, are presented in this report. International Organization for Standardization (ISO) standards 14040:2006 and 14044:2006 were mainly used to develop these guidelines. A brief literature review on pavement LCAs in the field of air transport is presented in section 2. No detailed or well-scoped airfield pavement LCA study was found in the literature review. Section 3 provides guidance on the goal and scope phase of an LCA. In this phase, the LCA's goal is defined precisely to clearly identify what questions must be answered, the study's system boundaries are established, and the functional unit that will be used throughout the study is determined. Section 4 provides guidance on the life-cycle inventory (LCI) phase of an LCA. The steps involved in creating an LCI are defining the flows into and out of the processes that occur within the system boundaries and collecting the necessary data to quantify the relevant input and output flows. Section 5 provides guidance on the impact assessment phase of an LCA. The purpose of this phase is to translate the LCI's results into impact indicators for the natural environmental, human health, and resource depletion. Sections 3 through 5 also give several examples of the first three phases of an LCA. Section 6 describes the conclusions based on the interpretation process, and recommendations are presented and qualified based on the completeness, uncertainty, and representativeness of the data

and analysis used to support them. Section 7 describes the reporting process and the critical review process in an LCA. Section 8 presents four case studies performed following the guidelines to quantify and better understand the life-cycle environmental impacts of airfields with regard to specific questions. Section 9 presents a summary and recommendations for future work.

For the case studies, several airports were contacted across the U.S., and a number of possible case studies were discussed based on completed or ongoing projects at the airports. Most airports showed interest in being able to quantify the environmental benefits of using different asphalt and concrete additives and in using recyclable materials that reduce the use of new natural resources and energy to potentially reduce emissions. The airports also showed interest in being able to quantify the environmental impacts of different design alternatives, projects, and material designs for decision support. Following are the specific case studies:

- Use of warm mix asphalt (WMA) by John F. Kennedy International Airport with help from the Port Authority of New York and New Jersey

- Use of WMA and use of concrete mixes with recycled materials by O’Hare International Airport with help from Bowman, Barrett & Associates Inc.

- Use of WMA and reclaimed asphalt pavement by Boston Logan International Airport with the help from the Massachusetts Port Authority

- Comparison of alternative pavement designs by Nashville International Airport with help from Atkins

Five tasks are recommended to further develop airports’ ability to consider life-cycle environmental impacts in their decision-making:

1. Submit the LCA framework for outside review and critique.

2. Develop and deliver initial training to the FAA.

3. Develop a plan for establishing complete analysis capability for airports using the framework developed.

4. Develop a first-version LCA tool for airports.

5. Deliver outreach and training with the LCA framework.

1. INTRODUCTION.

1.1 BACKGROUND.

The United States (U.S.) has more than 19,000 airports (5,104 public, 14,263 private, and 288 military airports) ranging from large hubs to non-hubs and reliever airports [1]. Within these airports, there are airfields that consist of pavements such as runways, taxiways, aprons, aircraft and vehicle parking areas, as well as airside and landside roads that support the smooth, safe movement of aircraft and service/operation vehicles. These structures are typically paved with asphalt or concrete surfaces, while some are unpaved. Other civil airport infrastructure includes refueling systems, tanks and hydrant systems, drainage systems, lighting systems, fencing, landscaping, and other features needed for safe and efficient airfield operations.

The Federal Aviation Administration (FAA) has taken measures to improve safety, enhance efficiency, reduce costs, increase resilience, and improve the sustainability of the U.S. airfields infrastructure by using a life-cycle cost analysis (LCCA) methodology to quantify and reduce the economic resources needed for expanding and preserving the airfield system. Evaluation of environmental impacts using a life-cycle assessment (LCA) approach to support decisions regarding airfield infrastructure is not an FAA requirement. However, some airports have created or are interested in creating their own sustainability improvement plans either as a part of airport long-range planning (Sustainability Master Plans) or as a stand-alone process (Sustainable Management Plans) [2]. According to the FAA, “Both documents achieve similar objectives. They use baseline assessments of environmental resources and community outreach to identify sustainability objectives that will reduce environmental impacts, realize economic benefits, and improve community relations” [2].

Some airfield infrastructure case studies were conducted; however, a comprehensive framework has yet to be thoroughly developed. While the environmental impacts of the airfield infrastructure life cycles are generally much smaller than those of fuel burning during aircraft operations [3], those impacts can be considered as a part of an overall continuous improvement plan for airport sustainability.

The life cycle of any civil airport infrastructure feature will involve the decisions regarding its design, construction, maintenance and rehabilitation (M&R), reconstruction, operations, and eventual removal or reconstruction. These decisions will influence the environmental impacts that result from the materials production, construction, and durability of the features, which will in turn affect the frequency of M&R and the time to reconstruction, as well as the interaction of the features with aircraft, vehicles, and people. Further, in some cases, potential changes made to a system that are intended to reduce environmental impacts may cause unintended negative consequences that can only be identified when the concepts of system analysis and a life-cycle time horizon are included in the decision-making process. For these reasons, a life-cycle perspective is needed to examine the net environmental impact of decisions regarding airfield civil infrastructure.

LCA is a methodology used to identify and quantify the life-cycle environmental impacts of a product, process, or system. It involves the following:

- Setting the goals and scope for an assessment;
- Inventorying the flows of materials, energy, and other resources into the system, and the waste and pollution out of the system;
- Using the flows to calculate impact indicators;
- Interpreting the impact indicator values; and
- Reporting the results to support decision-making.

When applied correctly to civil infrastructure systems, LCA can be used for several purposes, such as comparing alternative decisions, benchmarking operations for comparison with future improvements and for comparison with peers, and analysis for any potential unintended consequences of a policy, practice, or decision. LCAs should be used in conjunction with other decision-making criteria and information to provide the best comprehensive decisions regarding design or operation strategy.

LCA can be used with different levels of detail at different decision points in infrastructure management and delivery, including asset management, conceptual design, and detailed design, materials, and construction specifications. In a low-bid project delivery system, the airport does not know the source of the material that will be used; however, often the most significant decisions have to do with the timing of M&R, treatment selection, structural design of new and rehabilitation pavement cross sections, choices for lighting, drainage and other airside infrastructure, and specifications for materials and construction.

An important use of LCA is to evaluate changes in practice, specifications, and designs that initially appear to reduce environmental impact, but actually may have a different result. For example, it is commonly assumed that increasing the content of recycled pavement materials in new pavement materials will reduce environmental impact. However, if the increased recycling approach results in a shorter life, then the life-cycle impact may be increased because of the increased replacement frequency. Similarly, requirements for use of minimum recycled content may increase life-cycle impacts if sufficient recycled materials are unavailable locally and must be transported long distances. An LCA evaluation can identify negative unintended consequences of well-intentioned changes.

As with any future analysis, there is uncertainty associated with prediction. This uncertainty should be considered when using LCA to support decision-making through sensitivity analysis and other techniques, which are part of the LCA process interpretation phase.

The life cycle of any civil infrastructure system on an airfield can be divided into stages (figure 1), with all the stages affected by decisions at the asset management and project design levels [4]:

- Materials stage—Acquisition and processing of raw materials, the processing of materials used in initial construction and those used for subsequent M&R, and preservation activities.

- Construction stage—Transportation, placement of materials and products, other construction activities, and any effects of construction on operations.

- Maintenance and Rehabilitation (and Preservation) stage—Material production and construction for preservation, maintenance, or rehabilitation activities.

- Use stage—Pavement effects and other features on the aircraft and vehicles using them, pavement-environment interactions, and the interactions of other features with the environment that can affect air, water, thermal, and other natural cycles and conditions.

- End-of-Life (EOL) stage—Applies to an entire infrastructure system or to a portion of the system that has failed, often defined as when the next reconstruction of the feature occurs, or its demolition, replacement, or abandonment.

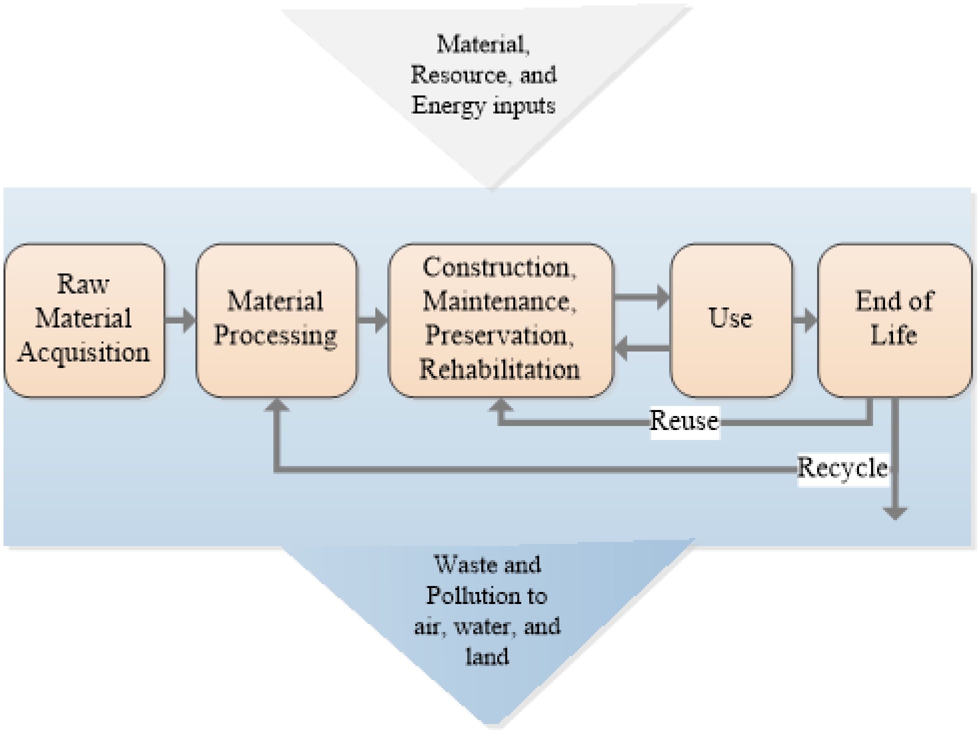


Figure 1. Pavement Life Cycle

The life-cycle stages that are ideally considered in an LCA are those that include all activities from cradle-to-grave, meaning from raw materials acquisition through the EOL stage. The LCA scope can also consist of a subset of these stages, such as cradle-to-gate, which only considers materials production and transport to the gate of a plant, and cradle-to-lay, which only considers materials, transportation to the construction site, and construction (discussed in section 3.4).

1.2 THE FAA LCA GOALS AND OBJECTIVES.

This report completes the first objective of a proposed three-phase program undertaken by the University of California Pavement Research Center (UCPRC) to develop an LCA model that the FAA can use to quantify the life-cycle environmental impacts of airfield pavements.

Each of the three phases has its own objectives:

- Phase 1

  Develop an LCA framework for airfields building on previously completed LCA development work for roads and highways, considering the unique scope of airfields; setup the analysis capability for the FAA within the framework; and review gaps in data and tools for the FAA to perform LCA for airfields. Perform initial case studies in order to demonstrate the use of guidelines and the framework.

- Phase 2

  Create a plan for filling the knowledge and data gaps and establishing LCA capability for the FAA. Perform outreach and training regarding LCA, and produce preliminary recommendations of practices to reduce the environmental impacts and enhance the sustainability of airfields based on the goals and scope of the initial case studies.

- Phase 3

  Develop the database and modeling processes that can analyze the environmental inputs and outputs with the capability to reflect regional technology and practices. Use the database and modeling process to develop a modeling tool and software that can be used to assist decision-making for airfield pavements.

The primary objective of this first-phase project is to develop an LCA framework that will support the FAA's capacity and capability to consider environmental impacts in decision-making. The framework is intended to function as a first version of a living document that will be updated as experience is gained from case studies and other development and implementation efforts.

The framework is intended for LCA studies evaluating decisions regarding the life cycles of the following features found inside the fence line of an airfield:

- Airside pavements
  - Runways
  - Overruns
  - Taxiways
  - Aprons (parking, power check, hangar access, wash rack, etc.)
  - Shoulders
  - Airside land vehicle roads

- Drainage
- Airfield lighting and other lighting
- Navigational aids
- Exterior fencing
- Maintenance of airside grounds

Specifically excluded are all landside and airside features, which include equipment related to aircraft servicing and fueling, fire suppression systems, wash racks and other cleaning equipment, gate operations, and all buildings. Pavement associated with these features is included in the LCA framework.

1.3 THE LCA PROCESS OVERVIEW.

The International Organization for Standardization (ISO) set up a series of standards for conducting LCA [5 and 6]. Based on the guidelines provided in ISO 14040 [5], the phases that should be included in an LCA are shown in figure 2.

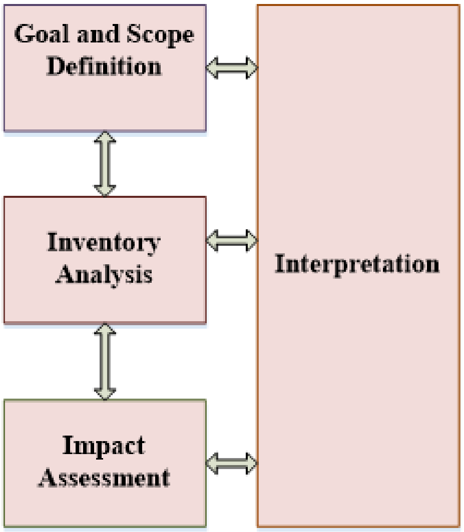


Figure 2. Phases for Performing an LCA

1.3.1 Goal and Scope Definition.

This first phase of an LCA is the goal and scope definition, which identifies its purpose, defines the system boundaries and functional unit to be analyzed, and identifies the approaches to be used in the analysis.

1.3.2 Life-Cycle Inventory Analysis.

The second phase is life-cycle inventory (LCI) analysis, which is considered the "accounting" phase. This phase involves modeling the processes in each of the life-cycle stages and the data collection for input and output flows. All the inputs and outputs related to the product and its environment are tracked, including the input of materials and other resources and energy, and the outputs of products and pollution. The inputs and outputs accounted for must fall within the defined system boundaries and are based on the functional unit defined in the first phase. Examples of inventoried items include primary resource consumption, waste flows, air emissions, and water pollutants resulting from the product over its life cycle.

1.3.3 Impact Assessment.

The third phase is the impact assessment phase, which provides additional information to help assess the environmental impacts within the life-cycle stages defined by the goal and scope definition phase by using the product's inventory results (flows) to calculate the resultant impacts on human and ecological sustainability. Most systems for calculation of impact indicators from the flows include indicators for the impacts to people and ecosystems, and the depletion of resources. The first step in this phase is to identify the inventory flows needed by the models used to calculate the selected impact indicators. For example, global warming potential (GWP) sums the various gases produced by a process and weights them by how much heat they trap in the atmosphere within a defined time period. The final step of impact assessment is valuation, which summarizes the results across the impact categories using weights or other approaches enabling decision-makers to assimilate and consider the full range of relevant outcomes. This step provides a basis for comparing different types of environmental impacts by their relative importance to the project.

1.3.4 Interpretation.

Interpretation phase is the fourth phase of an LCA. In this phase, the results of impact calculations are analyzed to draw conclusions and make recommendations to support the decision-making processes. Usually a sensitivity analysis and an uncertainty analysis are included to help determine the robustness and strength of the conclusions.

- Critical Review and Reporting.

  As required by the International Standards Organization (ISO) 14044 [6], an independent critical review is necessary, especially for comparisons that will be used in the public domain.

  Decisions also need to be made regarding how to effectively report the LCA results to meet the needs of the decision-makers and other stakeholders.

- Standardization of LCA for Civil Infrastructure and Outstanding Issues.

  LCA has been used to assess the environmental impact of many consumer products over the past 45 years, and has been applied to buildings and transportation fuels. It was first applied to pavement systems about 20 years ago, although most of the development for pavements has occurred since 2010. The pavement LCA development is ahead of all other civil infrastructure. Standards of practice for LCA, such as those published by ISO, are generic and high level to be able to cover all products, and they require extensive development for the details of a particular industry such as pavements and other airfield infrastructure to take them from academic studies into practice.

Performing an LCA on a long-life infrastructure feature such as a pavement can be much more complex than performing an LCA on a typical consumer product for a number of reasons, which include uncertainty regarding M&R decisions over the long life of the feature, uncertainty regarding interactions of the feature with vehicles and the environment if not trafficked, and what use stage factors to include in the assessment [7 through 9]. Until recently, due to a lack of consistent practice for LCA and the use of different data sources, the literature on pavement LCA sometimes produced conflicting answers to questions regarding the environmental impacts of pavement decisions. Work over the past 10 years to standardize LCA practice for civil infrastructure by developing guidelines with specific details relevant to this field has increased standardization of good practice and transparency.

However, there are issues that continue to require attention. Among them are how to decide the best approach to allocation of impacts when there are processes that produce multiple products and when there is reuse of products, how to address incomplete scope (missing life-cycle stages, most typically the use stage), and the lack of state-of-the-art models for some subprocesses in the pavement life cycle. Two major issues remaining are the need for more detailed data on specific civil infrastructure materials and consistent use of a transparent documentation system for showing how data are developed. Another issue, caused in part by the need for better flow data, is how to consider uncertainty. Many studies have assumed minimal uncertainty in data and process models, when in reality there may be a range of realistic values for a given process reflecting differences between materials sources, manufacturing processes, transport distances, construction practices, pavement structures and materials design practices, vehicle fleets, and a number of other variables that vary between projects, between regions, and over time [10 and 11].

The LCA methodology must consider uncertainty and gaps in information when it is used in the decision-making process. Lack of a life-cycle view, limited information, and the failure to consider uncertainty can sometimes make a decision appear to be environmentally beneficial, while a further, more complete analysis may reveal the opposite.

General guidelines for LCA were produced by the ISO in ISO Standards 14040 and 14044 [5 and 6]. Guidance for performing LCA for the purposes of producing an Environmental Product Declaration (EPD) for civil building materials was published by the European Committee for Standardization [12]. In 2010, the UCPRC hosted a Pavement Life Cycle Assessment Workshop in Davis, California [13 and 14], which produced an initial LCA framework that included standard assumptions, system boundaries, and documentation requirements for application of LCA to pavements [14]. Further symposia/workshops were held in Nantes, France in 2012 [15], in Davis, California in 2014 [16], and in Champaign, Illinois in 2017 [17]. The British Standards Institution published a specification for the LCA of greenhouse gas (GHG) emissions in 2011 [18]. The Federal Highway Administration (FHWA) recently prepared and published guidelines for pavement LCA in 2016 [19]. The guidelines for the FAA build upon the previous efforts described in this section.

1.4 APPLICATIONS AND COMPLEXITY OF LCA.

It is important to note that the current use of LCA in North America for the features of airfield is rather limited, and only a few agencies are preparing to apply LCA in a consistent way. That said, there are examples available, and they show that LCA can be used for a variety of purposes.

1.4.1 Example Applications.

Some examples of how agencies have applied pavement LCA are shown in table 1, which is adapted from ISO [5 and 6] and FWHA framework [19]. Using the categories shown in table 1, the most common current uses of LCA in North America are:

1. Selection of a material or pavement structural design in conjunction with LCCA (1.a.)
2. Identification and evaluation of the impacts of potential changes in a policy or specification (2.b.)
3. Development and application of LCA tools for screening and/or detailed LCA for the scoping and/or design of a project (2.e.)
4. Identification and evaluation of scenarios for network-level (facility-level for airfields) decisions and strategies for preservation, M&R (3.a.)
5. Development of pavement material EPDs (4.a.)

Table 1. Use Cases of LCA by Agencies

ISO Use Cases	Examples
1. Identification of opportunities to improve the environmental performance of products at various points in their life cycle.	a. Material or structural design selection (in conjunction with LCCA). b. Material procurement optimization. c. Evaluation of the potential benefits of the use of higher recycled content or on-site recycling of materials.
2. Communication and guidance for 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.	a. Identify the effects of potential changes in a project. These are typically comparisons of alternatives for material types and sources, pavement structural designs, pavement or other infrastructure basic type, design lives, future M&R scenarios, or other types of project-specific plans and specifications. The project can be for a new feature, 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 or new feature. b. 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 facility-level goals that will be applied across all projects and scenarios for facility 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 and/or the facility for the purposes of deciding whether or not to make the change. This type of study would typically be done by an engineer or planner to answer questions posed by internal or external stakeholders before moving ahead with changes. c. External communication of improvements in pavement and other feature life-cycle design and use by comparing environmental performance over time (current project vs. projects from before). d. LCA-based environmental performance as part of the procurement process in the design-bid-build (low-bid) project delivery system, being used in some European countries. e. Development and application of LCA tools for screening and/or detailed project-level LCA.

Table 1. Use Cases of LCA by Agencies (Continued)

ISO Use Cases	Examples
3. Selection of relevant indicators of environmental performance from a system-wide perspective.	a. Identification of relevant and significant environmental indicators that an agency has control over from a facility-level LCA approach. This type of study focuses on decisions or scenarios regarding timing and types of preservation, maintenance, rehabilitation, and reconstruction treatments for a set of features that are managed as a network on a facility-wide basis, such as a pavement, aircraft/vehicle-pavement interaction, fuel burn, fencing, drainage, or lighting network, or landscape maintenance of unpaved areas. This type of study would typically be performed by or for the management staff for that set of features in order to answer questions posed to the management unit internally or by external stakeholders regarding the entire facility or subsets within the facility. b. Prioritize LCI database development, either state (regional) or national.
4. Quantification of information on the environmental performance of a product or system (e.g., to implement an ecolabeling scheme, to make an environmental claim, or to produce an EPD statement).	a. The development of an EPD following the Product Category Rules (PCRs) for the product that is the subject of the EPD. b. While some of the materials that are used for airside features have EPDs that were published or are in the process of being published, databases are not currently available in the U.S. market for environmental flow and impact information on complete systems for pavement, fencing, drainage, etc. It is generally expected that this will remain common in North America because the complete systems are generally individually designed for the unique conditions for each project. They are also often designed by the owner rather than the producer without knowing the precise source of the materials, and therefore cannot be assessed with an EPD for a complete system.

1.4.2 Levels of Complexity.

It is important to note that every LCA study should be defined in the goal and scope definition phase. The chosen approach should always be kept in mind when drawing conclusions during the last phase of LCA, the interpretation phase. This also means that the level of detail required within some sections of this report depends on what the study is trying to accomplish. Each phase of the LCA process, and the steps within these phases, will depend on the intended purpose of the study. There are three levels of LCA application, and they can be conceptualized in terms of their complexity. Each application demands a particular level of data gathering, impact calculation, determination of what to include or exclude, and precision of the data included in the study. The application types can be broadly grouped into the following categories:

- Benchmarking study—this type of LCA is intended to provide initial results for comparison of alternative decisions. It will often be limited to defining the goal and system boundaries, determining the flows of materials and resources going into the system and the products, wastes, and pollutants coming out of it, and comparing those results quantitatively. This type of study can also be limited to only focus on the changes between the different alternatives. A benchmarking study includes inventory data such as those for energy, emissions, and waste, but does not usually include impact assessment. This type of study is not considered a full-scale LCA, but it begins the process of applying LCA methodology to decisions.

- Limited-scope LCA study—this type of study only considers a few impact indicators, and may or may not consider the complete life cycle. Limited-scope studies include the development of LCIs and life-cycle impact assessment (LCIA). Current pavement LCAs tend to fall in this category as they look mostly at energy flows and GHG emissions for the full life cycle. For example, a carbon footprint would only consider the materials, or the materials and construction stages, and only calculate the global warming impact indicator from GHGs. A limited-scope LCA will include a sensitivity assessment even though the study’s interpretation phase may include less detail than is called for in a more comprehensive LCA. It is also important for transparency reasons that this LCA type completely document its limitations.

- Complete LCA study—a complete LCA study includes LCI, LCIA for a larger set of impact indicators, and interpretation, and it considers the complete life cycle of the feature. Often referred to as a full LCA, the study is generally required for EPDs as called for in PCRs, except that the life-cycle stages only go from cradle-to-gate of the producer’s plant. It is expected that over time there will be more complete LCAs developed in North America.

The following steps can be taken to begin including LCA concepts in decision-making even without following the full LCA process:

1. Identify the questions to be answered and the specific environmental goals to be achieved. The questions to be answered by LCA studies generally fall into three categories:

   a. What is the impact of a change in policy?
   b. How is a facility or set of features best managed?
   c. How can the design of a specific project be improved?

   In many cases the questions to be answered include comparison of new alternatives with current practice, considered as a base case.

2. Define the system boundaries, identify what items are the same across a comparison study, and determine where to possibly eliminate the need to consider them in the analysis.

3. Define the functional unit(s) and the approach required for sensitivity analyses (specific project variables or a number of cases for evaluating a policy that spans the expected ranges of conditions).

4. Identify the types of operations and materials that occur within the system and how their type and numbers change for the options being considered. (At this point, a comparison of the number 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 the appropriate environmental data sets (LCI data) needed and continue with the LCI analysis, impact assessment, and interpretation phases of the LCA as described previously.

The completion of the first four steps of this process can often identify whether the rest of the LCA needs to be completed because of the potential complexity of the answer, or whether it is clear that one alternative will have a reduced environmental impact [20].

1.4.3 Matrix of Applications and Complexity.

The guidelines presented in this report cover all of the applications and levels of complexity described in sections 1.4.1 and 1.4.2. A summary is presented in table 2.

Table 2. Matrix of Applications and Complexity

Application	Benchmarking (Calculation of flow quantities for full or partial life cycle)	Limited Scope LCA (Calculation of small set of indicators and or partial life cycle)	Complete LCA (Calculation of full set of indicators and full life cycle)
Identification of opportunities to improve the environmental performance of products at various points in their life cycle.	Can provide initial, rapid information for evaluating relatively simple questions. Can be used as conceptual evaluation tool prior to LCA.	Used for narrowly defined questions that consider only a limited set of indicators or life cycle stages. Unintended consequences of decisions may occur because important indicators or life-cycle stages were not included.	Provides a more complete answer, and less risk of unintended consequences. More costly and time-consuming; may have problems obtaining high-quality data and/or impact calculations.
Communication and guidance for 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.	Generally insufficient, except for simple evaluations of processes and designs.	Used for narrowly defined questions that consider only a limited set of indicators or life-cycle stages. Unintended consequences of decisions may occur because important indicators or life-cycle stages were not included.	Provides a more complete answer, and less risk of unintended consequences. More costly and time-consuming; may have problems obtaining high-quality data and/or impact calculations. Should be used for major policy changes and for large, expensive projects.
Selection of relevant indicators of environmental performance from a system-wide perspective.	Generally not applicable.	Used for narrowly defined questions that consider only limited set of indicators or life-cycle stages. Unintended consequences of decisions may occur because important indicators or life cycle stages were not included.	Provides a more complete answer and less risk of unintended consequences. More costly and time-consuming; may have problems obtaining high-quality data and/or impact calculations. Should be used for major policy changes and for large, expensive projects.
Quantification of 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 EPD statement).	Not applicable.	Commonly used for EPDs. For broader questions and more complex systems, unintended consequences of decisions may occur because important indicators or life-cycle stages were not included.	Generally not used for materials declarations because it is not able to define performance in a larger system (pavement structure or drainage system, for example) or for the use stage. Generally used in design-build or design-build-maintain projects where the use stage is calculated. Can be used in design stage of design-bid-build project using assumed materials and construction processes.

2. LITERATURE REVIEW.

The FAA has continually sought both to improve the safety and sustainability of aviation infrastructure as well as to reduce the costs associated with maintaining U.S. airfields. In 2010, the FAA proposed its Airport Sustainable Master Plan Pilot Program to enable the agency to develop and implement guidelines for airport sustainability [21]. Several airports, ranging from large hubs like Denver International and Newark Liberty International airports, to small regional or municipal airports, like Fresno Yosemite International and Newport News/Williamsburg International airports, have already participated in the FAA's [22] sustainability plans to reduce environmental impacts and improve local community relationships in planning and operational objectives.

Many U.S. airports that include Philadelphia International Airport [23], Louis Armstrong New Orleans International Airport [24], Columbia Regional Airport [25], Bolingbrook's Clow International Airport [26] have also taken steps to address environmental concerns. Some airports, such as Chicago O'Hare International, San Diego International, the Los Angeles World Airports system, Boston Logan International, Dallas Fort Worth International, and Seattle-Tacoma International are implementing sustainability practices [27]. Carlini [27] investigated the sustainability practices of large hub airports and concluded that substantial benefits were achieved, including reduced life-cycle costs, greater asset utilization, new and better technologies, and reduced environmental health and safety risks.

Along with economic and social considerations, environmental considerations are an important aspect of sustainability. Although potential improvement in some aspects of a system's sustainability may help reduce environmental impacts, there may be unintended negative consequences that occur in other parts of the system being improved earlier or later in the life cycle of the system, resulting in a negative total impact on environmental sustainability. Therefore, a thorough system definition and a life-cycle perspective are necessary to evaluate and/or assess the ecological part of sustainability. Other studies, such as those by Chester [3], Kulikowski et al. [9], the Airport Cooperative Research Program (ACRP) [28], Uppenberg et al. [29], and Lewis [30] have already highlighted the importance of a life-cycle approach for environmental assessment of airport infrastructure.

The life-cycle environmental impacts of a product, process, or system can be identified and quantified using LCA methodology. This methodology involves setting a goal and scope for an assessment, inventorying the flows of materials and resources that go into a system and the waste and pollution that come out of it, assessing flows to impact indicators, and interpreting the impacts to support decision-making regarding changes in the system intended to improve environmental sustainability. Life-cycle studies by definition cover the stages that go from cradle-to-grave. Where later stages are not part of the system being analyzed, often because they are outside of the scope of decision-making, studies may only consider materials extraction, production, and construction, and are called cradle-to-lay, or may only consider materials extraction and production, and are called cradle-to-gate. For airfield pavements, an examination of the use stage includes the pavement effects on aircraft, such as damage and increased fuel consumption, and the pavement effect on other processes, such as air conditioning use, storm water treatment, and lighting.

LCA can include consideration of a wide range of pollution and resource use flows, as well as impact indicators, or be limited to a few flows and indicators if a more limited scope of questions is being posed. For example, a carbon footprint study only considers GWP, which is communicated in terms of equivalent units of carbon dioxide equivalent (CO_2-e).

A summary of the focuses identified in different published airfield life cycle studies is shown in table 3, which points to specific literature sources [28 through 42], followed by a brief literature review. The literature contains far fewer LCA studies of airfield pavement and other airfield infrastructure than of other types of transportation infrastructure. Most of the existing literature examining airfields with a life-cycle perspective has focused on comparing various transportation modes [28 through 33] or LCCA [34 through 36]. The remaining articles available were environmental assessments [24 through 26] or focused specifically on GHG emissions [23, 28, and 37].

Few comprehensive studies address environmental concerns from a life-cycle perspective. Uppenberg et al. [29] from the IVL Swedish Environmental Research Institute used LCA methodology for EPD development of infrastructure systems, including airports. The models developed included the production, operation, and maintenance of infrastructure systems, and focused mainly on railways and airfields (embankments, runways, taxiways, parking stands, terminal buildings, peripherals, electrical installations, etc.) for a span of sixty years. The LCA model used for the pavement aspects came from Stripple [38].

The impact categories included resource usage (nonrenewable, renewable, electricity), emissions (eutrophication, GHG, ozone depletion, ground ozone, acidification, aquatic oxygen depletion), and waste generation. Infrastructure was the largest contributor of GHG emissions, eutrophication potential (EP), acidification potential, and the formation of ground-level ozone during the airport construction and operation. The use of nonrenewable materials was the most important impact for the construction works (including runways and taxiways).

A detailed life-cycle inventory (LCI) of passenger transportation modes including an assessment of vehicles, infrastructure, and fuel components was performed by Chester [3]. The scope of the study included the construction, maintenance, and operation of airport infrastructure, with energy, GHG emissions, and air pollutants as the indicators. The Economic Input-Output Life-Cycle Assessment (EIO-LCA) [43] and Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) [44] LCA tools were used for the airport infrastructure inventory analysis. The study also evaluated three different aircraft (Embraer 145, Boeing 737, and Boeing 747) with the functional unit defined as including aircraft life, passenger miles traveled, and aircraft miles traveled.

A few other studies also addressed airport infrastructure using LCA. A study by Lewis [30] carried out an LCA study of a Norwegian passenger air transport system, which included the airport infrastructure's construction and use (operation) stages. The study used a hybrid LCA (process-based LCA and EIO-LCA) and three functional units (passenger kilometers traveled, aircraft kilometer traveled, and aircraft lifetime). Kulikowski et al. [9] developed an LCA tool called LCA-AIR to perform LCA analysis of airfield pavements from material production through the use stage. Further, Kulikowski [31] used LCA-AIR to evaluate three rehabilitation strategies (reconstruction, rubblization with mill and asphalt concrete inlay, and precast concrete panel) for Taxiways A and B at O'Hare International Airport in Chicago. Facanha and Horvath [32] also used a hybrid LCA to develop the LCI of air emissions (CO_2, nitrous oxide (NO_x), particulate matter smaller than 10 micrometers (PM_{10}), and carbon monoxide (CO)) that are associated with goods transportation, including air transport. It included the construction, M&R, use (operation) and EOL stages.

Horvath and Chester's [42] study found that infrastructure construction, use (operation), and M&R stages account for 12%, 12%, and 3% of life-cycle energy consumption and 16%, 12%, and 2% of GHG emissions, respectively. Energy and emissions that were associated with pavements (taxiways, runways), buildings, operation of facilities, insurance, and other subsystems were also considered. Mosier et al. [34] came up with a measure of a carbon footprint cost index. They concluded that practitioners should "invest in the treatment types themselves and take pavement preservation and maintenance to an even higher level of sustainability by selecting treatments that minimize the impact to the environment" [34]. It was found that "little, if any, existing research has addressed sustainability through preservation practices for the taxiway, runway and landside pavement" [34].

Although a pavement LCA framework and guidelines for airfields are needed for the FAA to evaluate the environmental sustainability of airfield pavement projects, detailed, well-scoped airfield pavement LCA studies were unavailable. This type of guideline would also be beneficial for the FAA in determining environmentally sustainable options, from a life-cycle perspective, for runways, overruns, taxiways, aprons, parking areas, and other pavement structures.

Table 3. Studies Related to the Environmental and/or Life-Cycle Impacts of Air Infrastructure

Study	Purpose	Infrastructure Considered	Stages Considered (for life-cycle studies only)	Other Environmental Studies
Heathrow Airport Limited (HAL) [39]	An extension to the existing Heathrow Airport	Airport (runway)		Carbon footprint assessment
ACRP [28]	Handbook for GHG emission reduction strategies	Airport		GHG emissions
ACRP [40]	Sustainable airport construction practices	Airport		
Carlini [27]	Implementing sustainable practices in the U.S.	Airports		
Chester [3]	LCI of vehicles and infrastructures	Automobiles, buses, heavy and light railway transit, and aircraft		LCI
Mosier et al. [34]	Airport pavement sustainability	Airport pavement		Carbon Footprint Cost Index (LCCA)
Applied Research Associates [36]	Airport pavements	Airport pavements	Construction, M&R activities	LCCA
Uppenberg et al. [29]	EPD for transport infrastructure systems	Railway and airport		
Hansen et al. [41]	Comparative evaluation of GHG emission reduction strategies	Maritime and aviation		
Columbia Regional (COU) Airport [25]	Environmental assessment	Airport (Columbia, Missouri)		EA
New Orleans Aviation Board (NOAB) [24]	Environmental assessment	New Orleans Aviation Board (NOAB) [24]	Environmental assessment	New Orleans Aviation Board (NOAB) [24]
Monsalud et al. [37]	Sustainability feasibility for U.S. airports	Monsalud et al. [37]	Sustainability feasibility for U.S. airports	Monsalud et al. [37]
Facanha and Horvath [32]	Environmental assessment of freight transportation in the U.S.	Facanha and Horvath [32]	Environmental assessment of freight transportation in the U.S.	Facanha and Horvath [32]

Table 3. Studies Related to the Environmental and/or Life-Cycle Impacts of Air Infrastructure (Continued)

Study	Purpose	Infrastructure Considered	Stages Considered (for life-cycle studies only)	Other Environmental Studies
Lewis [30]	Assess environmental impacts of passenger air transport	Lewis [30]	Assess environmental impacts of passenger air transport	Lewis [30]
New Orleans Aviation Board (NOAB) [24]	Environmental assessment	Louis Armstrong New Orleans International Airport		EA
Monsalud et al. [37]	Sustainability feasibility for U.S. airports	Airports (mainly operations)		GHG emissions framework
Facanha and Horvath [32]	Environmental assessment of freight transportation in the U.S.	Road, railway, and airport	Construction, use (operations), M&R and EOL	LCI of air emissions (CO_2, NO_x, PM_{10}, and CO)
Lewis [30]	Assess environmental impacts of passenger air transport	Airport	Construction and use (operations)	LCA
Philadelphia International (PHL) Airport [23]	GHG emissions	Airport		GHG emissions inventory
Bolingbrook's Clow International Airport (IC5) [26]	Environmental impacts	Airport		EA
Horvath and Chester [42]	Energy, GHG, and criteria pollutant inventory	Railway and airport	Construction, use (operation), and M&R	LCI
Kulikowski et al. [9]	Develop LCA tool for airfield pavements	Airport (runway, taxiway, apron)	Materials, construction, M&R, and use stages used in airport pavements	LCA
Kulikowski [31]	LCA of rehabilitation strategies for taxiway pavements.	Airport taxiway	Material, construction, M&R, and use stages used in airport pavements	LCA

Notes:
NO_x = Oxides of nitrogen
PM_{10} = Particulate matter 10 micrometers or less in diameter
CO = Carbon monoxide

3. GOAL AND SCOPE.

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

Once the goal of the study is defined, the scope is defined to include the following items [5 and 14]:

- Definition of the product (or products) to be studied in terms of the function or service it provides.
- 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 subsequent interpretation to be used to address the goal, with environmental indicators including selected aggregated flows from the LCI 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 limitations of 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 presented in detail in this section. Short introductions are also provided regarding how the remaining items should be considered in the goal and scope definition process, with more details on data inventories and allocation, impact assessment, interpretation, critical review, and reporting presented in later sections.

The process for developing the goal definition and scoping document works best if it follows, in order, a sequence like that shown in figure 3 [19]. Assumptions and limitations should be documented in each step of the goal setting and study scoping process for use in steps 7 and 8 shown in figure 3.

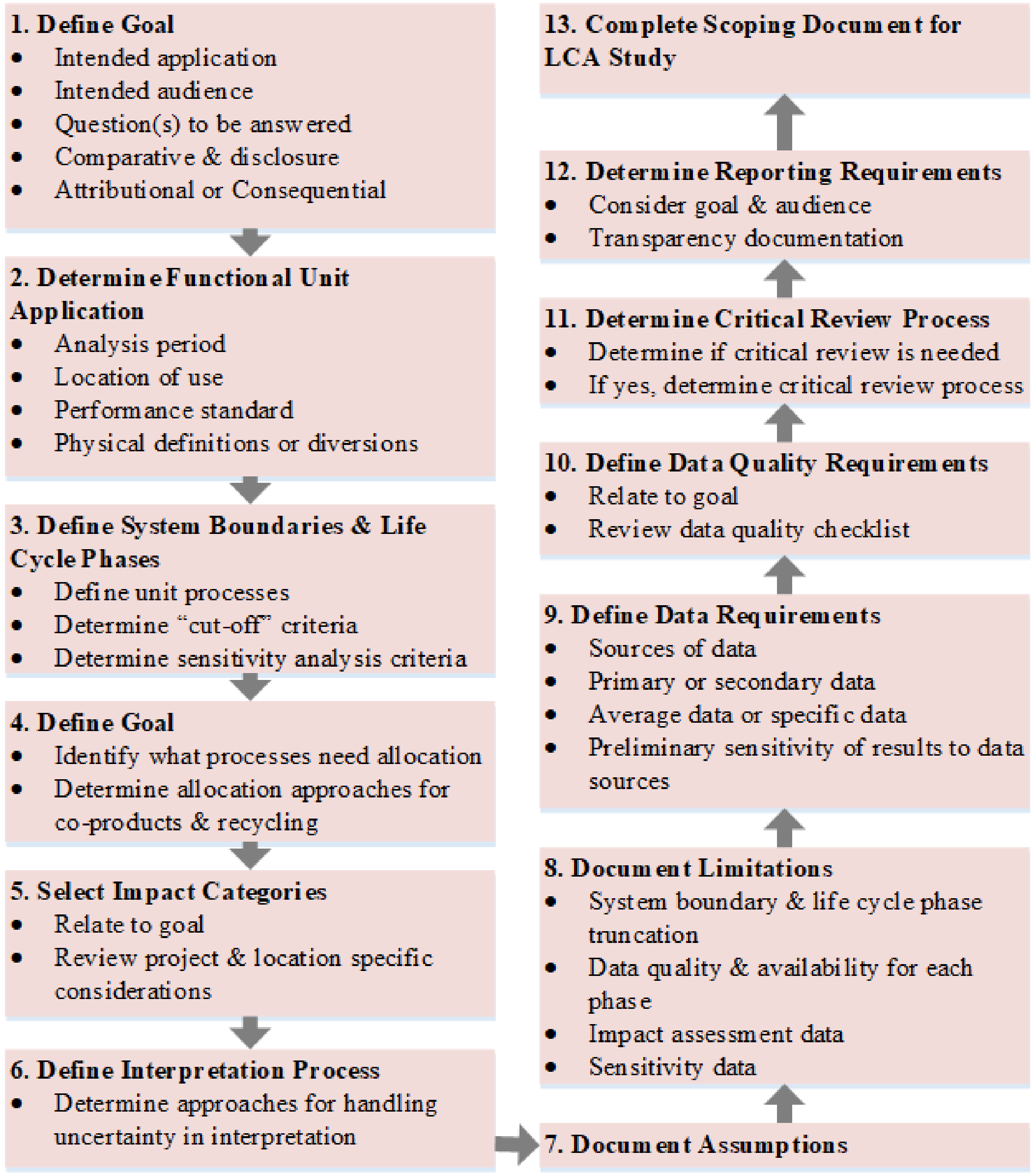


Figure 3. Development of Goal Definition and Scoping Document for LCA Studies

The process for goal and scope definition shown in figure 3 should be used for all types of studies shown in the matrix in table 2. As defined for this document, benchmarking studies are generally considered to include all steps shown in figure 3, except that in some cases only flows (units of materials and construction) are considered without translating those into impact indicators. In those cases, step 5 in figure 3 would include selection of which flows to consider instead of which impact indicators.

3.1 DEFINE GOAL.

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 section and subsequent sections.

Consider these items when defining the goal of the study:

- Intended application
- Intended audience
- Question(s) to be answered
- Whether the study is a benchmark study or a project- or facility-level study (for each level, system boundaries, and the importance and availability of data, and data quality may change)
- Whether the study is intended for comparison of alternatives in a comparative study, or for disclosure of a single decision or product
- Whether the study approach is attributional or consequential

The primary audience for most airfield LCA studies will be airfield practitioners and those working with them in delivering and operating airfield pavement systems, including the FAA. This can span designers, maintenance managers, material and construction engineers, inspectors, and planners who are responsible for the design, construction, and preservation of airfield pavement networks. Other key stakeholders in the airfield pavement community expected to benefit from the information contained in an airfield LCA study can include nonfederal airports, military airports, industry (suppliers, producers, contractors, and consultants), academia, and various public interest groups. Outside of the people directly involved, the general public is often interested in how their local airport is performing as are the people who live near an airport and want to know the consequences of efforts to reduce the environmental impact of the airfield.

Regarding comparative LCAs, ISO 14044 states the following:

> 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, 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. [6]

LCA studies can take either an attributional approach or a consequential approach depending in part on the goal(s) of the study. The attributional approach is retrospective, whereas the consequential approach is prospective. 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" [5]. This is useful in understanding the impacts of a pavement project, but may not be appropriate when considering future policies or technologies, particularly those that change the status quo. These types of change-oriented studies should take a consequential approach.

Consequential LCAs (CLCAs) evaluate the environmental impacts of changes to the system being evaluated, which can be useful in evaluating system-wide impacts. Additionally, CLCAs can be useful for infrastructure and traffic planning studies that evaluate decisions that have longer-term and more far-reaching consequences. Attributional studies should generally include all life-cycle stages to capture the full environmental impact. A less-than-complete life cycle can be responsibly modeled if the goal and scope are clearly defined to only consider certain stages, such as for an EPD or benchmarking study, or if a consequential study is comparing alternatives that have some stages or other parts of the process in common. System boundaries should be set to capture "unintended consequences" and interactions of the pavement processes being assessed with other systems.

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. Thus, the goal of the pavement LCA can be any of the following four options:

- A single-product analysis to determine the flows and impacts of the product or system.
- A single-product or system-consequential analysis that considers how flows and impacts will change beyond the system in response to decisions.
- An attributional comparison analysis, comparing the flows and impacts of two or more products or systems.
- A consequential comparative analysis, comparing the changes in flows and impacts of alternative decisions.

Most pavement LCA studies are attributional because most of the common uses of LCA in pavement 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. Examples of the four types of pavement LCA studies are shown in table 4 [19].

Before moving to the next step in the developing LCA study, the sponsors and the practitioner should review the goal definition statement to be certain that it is fully understood and that they agree on its accuracy, and that the problem under investigation is accurately presented. If the study’s goal changes, the study will need to be redesigned since the goal will determine the scope of the analysis.

Table 4. Types of Pavement LCA Studies

Question	Type of LCA Study	Intended Application	Intended Audience
What are the resource flows used in production of an airfield pavement material and 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 for an existing taxiway 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 transportation required by sourcing pavement materials from alternative locations?	Comparative attributional (Benchmarking study, no impact indicators calculated, only LCI for flows of interest)	Select alternative locations and alternative available transportation modes (truck, rail, or barge) for sourcing materials for airfield	Construction planners and project managers, local residents, and permitting and other government agencies
What are the changes in airside vehicle replacement time based on wear and tear from pavement condition (vehicle wear and tear is generally outside the pavement system) for different levels of maintenance, and what are the environmental impacts of the change in replacement time?	Single-system consequential	a. Decision support for a single project, b. Decision support for a facility scenario, or c. Policy analysis	a. Sponsors of a project design, b. The agency managers overseeing a pavement management system, or c. An engineer evaluating changing construction smoothness requirements
What are the life-cycle environmental impacts of changing specifications for airfield asphalt or concrete mix designs to include recycled materials considering alternative uses of the recycled materials and the replaced asphalt and cement binder outside the airfield pavement system?	Comparative consequential	Determine whether the policy produces environmental benefits compared to the current specifications based on analysis of a set of representative mix designs	Policy decision-makers, industry groups affected (within and outside of pavements)

3.2 DETERMINE FUNCTIONAL UNIT OR DECLARED UNIT.

The functional unit selected for an airside infrastructure LCA will depend on the scope of the study. Careful consideration must be given to the functional unit to be certain that the goal of the study will be correctly answered. For comparative studies, the functional unit must be defined to provide a fair and complete comparison. The scope of this guideline only considers infrastructure systems within the fence line. A list of suggestions for what should and should not be included in an airfield LCA can be found in table 5.

Table 5. Examples of What is Included and What is not Included for Airfield LCA Development

Included in LCA for Airfields in This Document	Not Included in LCA for Airfields in This Document
• Runways • Taxiways • Aprons • Drainage • Fences • Parking areas (inside fence area) • Airside airport land vehicles • Aircraft • Land use • Signs and pavement markings • Pavement lighting	• All landside features and operations • Planning • Capacity • Barriers and other safety appurtenances • Ice and snow management • Landside airport land vehicles • Bridges and other structures • Buildings and terminals

The functional unit defines the system that will be studied. The definition of the functional unit includes identifying the following items:

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

For airfield infrastructure systems, the functional unit should be a representation of the physical dimensions and the quantified performance of the feature, 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” [6]. The functional unit acts as the reference for scaling of input and output data in any of the life-cycle stages of the product or service [12 and 45].

Whenever the goal of the study is to compare alternatives, it is essential that there is equivalence in their definitions of the functional units so that they can be compared without bias. The function is defined as a service provided by the system or the performance characteristics of the product. ISO 14040 defines a functional unit as the “quantified performance of a product system for use as a reference unit” [5]. For pavement systems, the functional unit should be a representation of the physical dimensions and performance of the pavement [14]. The functional unit is the means for quantifying the product function, the basis for the LCA study, and the reference for normalizing input and output data [45]. The functional unit is used to normalize the LCA so that comparisons among alternatives can be made.

The functional unit used for modeling processes in LCA should have a similar scale so it is applicable to the study's goal and typical of its intended application. Normalization to a convenient size for comparison or communication should only be performed 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 runway work should be scaled to match that of a typical project size so it can be normalized later in terms of a convenient unit for comparison and communication (e.g., square yards of pavement surface, etc.). However, defining the functional unit as 1 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 more useful to define the functional unit at the application level that defines the service for the end user. Therefore, pavement functional units tend to include a full pavement, which can be expressed in surface area that has to function for a period of time. Similarly, units for drainage, fencing, signage, etc. should be modeled first at the full scale and then normalized to a standard-scale unit (standard unit distance of fence, etc.).

Some studies normalize functional unit physical dimensions after full-scale modeling is completed to make it more comprehensible for the audience or to make it easier for comparison (for example, by taking the feature-width or project-length functional units and then normalizing them into a unit of volume). Normalization of the functional unit into volume for the materials stage could be reasonable, but it does not have meaning in the use stage where the length of taxiway or area of apron is much more relevant.

Comparison of different alternatives between airports or between features on an airfield should consider the loading for which the feature is intended to provide service. Examples are the number of takeoff or landing operations for similar types of aircraft (appropriately divided by classes of gear type and loads for example), the number of landside ground vehicle passes, and the number of gate operations at an apron, etc. Recommendations and examples that apply to airfields are as follows:

- Materials—the functional unit for materials, such as concrete and asphalt mixtures, can be defined as a unit mass or volume of material.

- Pavements—the surface area of pavement (mainline and shoulder of runways, taxiways, aprons, overruns, and airside roadways) to be considered is the recommended functional unit. The design life must be defined, or preferably, a functional life, including subsequent maintenance, rehabilitation, and EOL.

- Parking lots, apron pavements, and landscapes—square footage of area that is designed for a lifetime of *N* number of years could be considered.

- Drainage system—the functional unit for a drainage system is defined as a volume of runoff conveyed over the structure's lifetime. More specifically, the functional unit could be the management of 100 cubic ft of runoff in the drainage system over the design life of the system.

- Operations include lighting, sign boards, barriers (fences), and pavement markings—A functional unit similar to that for pavements or parking lots could be used; for example, the products used within a certain area that will have defined functionality for a defined life.

- Other functional units that could be used are:

    - Airport equivalent
    - Passenger equivalent
    - Cargo equivalents served (freight mass-distance)
    - Vehicles served

When the product application 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 LCA scope does not include all the life-cycle stages beyond delivery to the gate of the plant, and therefore, functional requirements for the stages will not be defined. The defined unit is typically described in terms of its physical quantity such as mass, length, areas or volume, and does not include any definitions of functionality. Defined units are used for EPDs for materials used in a number of applications, and they are used to provide LCI information for components of composite materials. The declared unit should relate to the typical albeit not completely defined uses of the material [12].

Defined units are often used for materials used in pavements such as aggregate, crumb rubber modifier, water-reducing agents, water, lime, asphalt binder, and cement, which can be used in different quantities in a number of different pavement materials prepared with different processes and having different functional requirements. They may have some properties that contribute to the final functional properties of the composite materials or infrastructure system they are used in, but they do not completely define the functionality of the final material or infrastructure system. It is recommended that declared units be in terms of the commonly used defining unit type (i.e., mass, volume, area or length, pavement design, procurement and construction) for their product family [12].

3.2.1 Application.

The application will determine the characteristics and components of the system based upon the purpose that it is intended to serve. The application, which is determined when defining the goal, is the subject of the goal question.

3.2.2 Location of Use.

The location of use will control the definition of a number of other elements of the functional unit and later decisions, such as applicability of data, and potentially 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 facility for a facility-level analysis. The owner of the functional unit will influence the standards being applied, the technology used for materials, prevailing construction practices, 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 where the product is produced. An EPD can be for a single site producing a material or an average, or a model representing multiple sites (see section 5).

3.2.3 Physical Boundary Definition and Dimensions of Functional Unit.

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

In general, a complete pavement system LCA study needs to consider the processes within the physical boundaries of the pavement structure, including surface, base, subgrade, shoulder, and drainage. 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 feature but leave shoulders 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 left out; or the slopes of fill sections may be included or left out depending on the goal of the study.

3.2.4 Performance Standard.

The performance standard for the pavement system(s) being evaluated is typically identified in terms of the design life, functional life, or functional criteria such as roughness or distress levels. 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 that it defines 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 metrics such as to a specified level of distress and/or roughness, or other structural or functional condition measures within a defined time period or defined number of traffic operations. They can play a crucial role in interpretation of the study, especially in comparative LCAs where two different products offering the same service are compared.

When the goal is a comparative study, ISO 14044 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. [6]

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

Some metrics used in comparisons, such as ride quality measured by International Roughness Index (IRI), friction, and others listed (with any appropriate measurement technology adjustments), can likely be assumed to be comparable between the different pavement types and other pavement decisions being considered. Other metrics may differ between pavement types because they only occur on one type, such as faulting on jointed plain concrete pavement, rutting on asphalt pavement, and the different types of cracking occurring on each pavement type. In the latter case, consideration of the agency’s definitions of comparable states for performance metrics should be identified in the goal and scope of the study, and comparison 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, operations, and climate relevant to the location, and the materials and construction standards and specifications of the owner and expected future M&R interventions. For comparison of alternative treatment scenarios in a facility-level LCA, the performance standard could include the agency’s decision-tree criteria for treatment, facility-level distress level 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/or provide test data that will permit the audience for the EPD to determine what standards and specifications it will meet.

3.3 DETERMINE ANALYSIS PERIOD.

For pavement LCA, the recommendations made for selecting the analysis period are intended to capture the impacts of the current decision and its influence on the subsequent maintenance/preservation treatments at least through the life of the next major rehabilitation or reconstruction treatment event, without unnecessarily increasing the analysis period and subsequently raising the difficulty and uncertainty of predicting future events.

When comparing different pavement design options, the analysis period should at least cover the pavement life up to the next major rehabilitation of the longest lasting system, and preferably 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. 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.

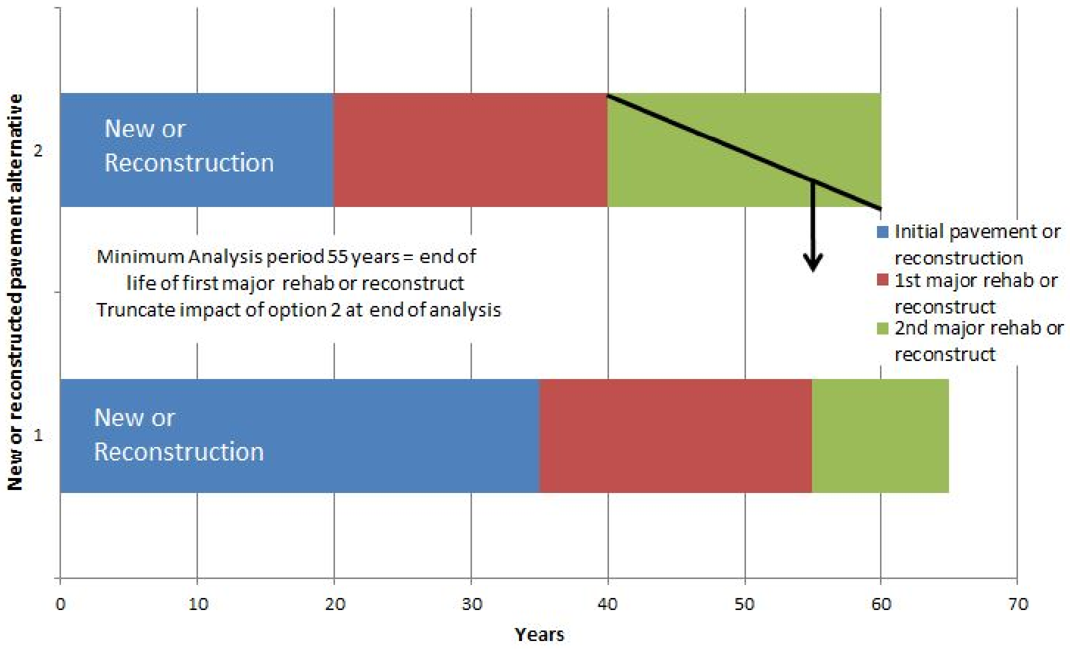
For pavements, a typical intended analysis period matches that of an LCCA to capture the performance of the initial product or service and its effect through the life of at least the next subsequent major rehabilitation treatment, and preferably through the lives of following rehabilitation treatments or the next full reconstruction.

The U.S. Department of Transportation (DOT) provides the following general guidance for highways:

> 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. [46]

The following examples illustrate how to apply recommended process for selecting analysis periods for comparison analyses.

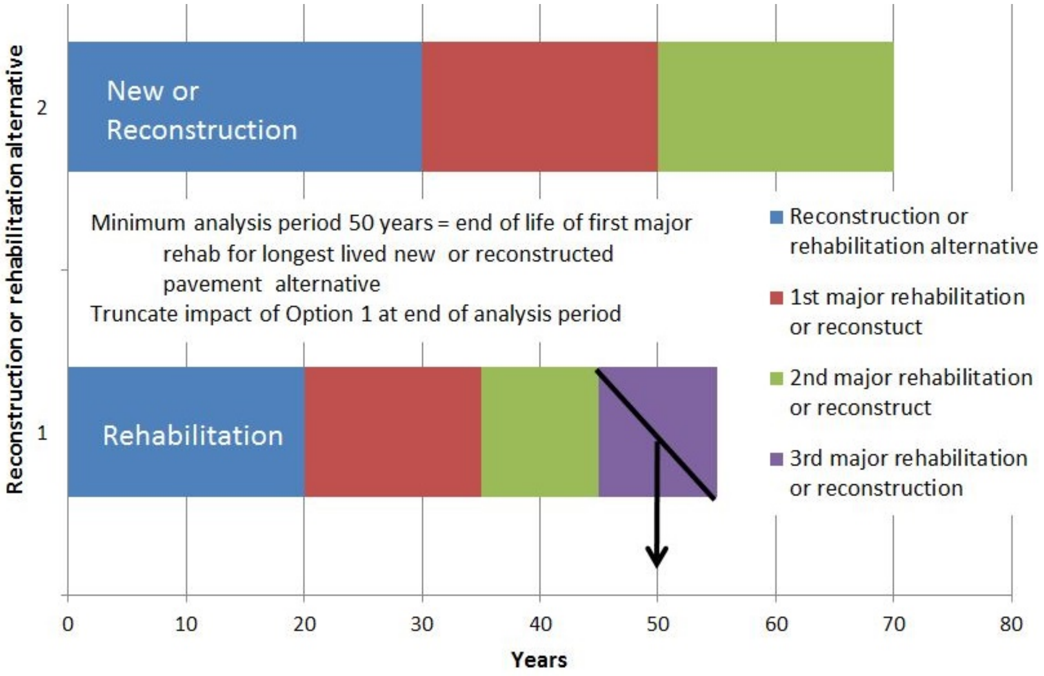
- When comparing two new pavements or pavement reconstructions (see figure 4):
    - The analysis period should be the time through the life of the first major rehabilitation or reconstruction of the longest-lived alternative.
    - The impacts of the shorter-lived alternative and all subsequent treatments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



Note: the arrow indicates truncation of the second 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 4. Minimum Analysis Period Recommendation for Comparing Two New Pavement or Reconstruction Alternatives

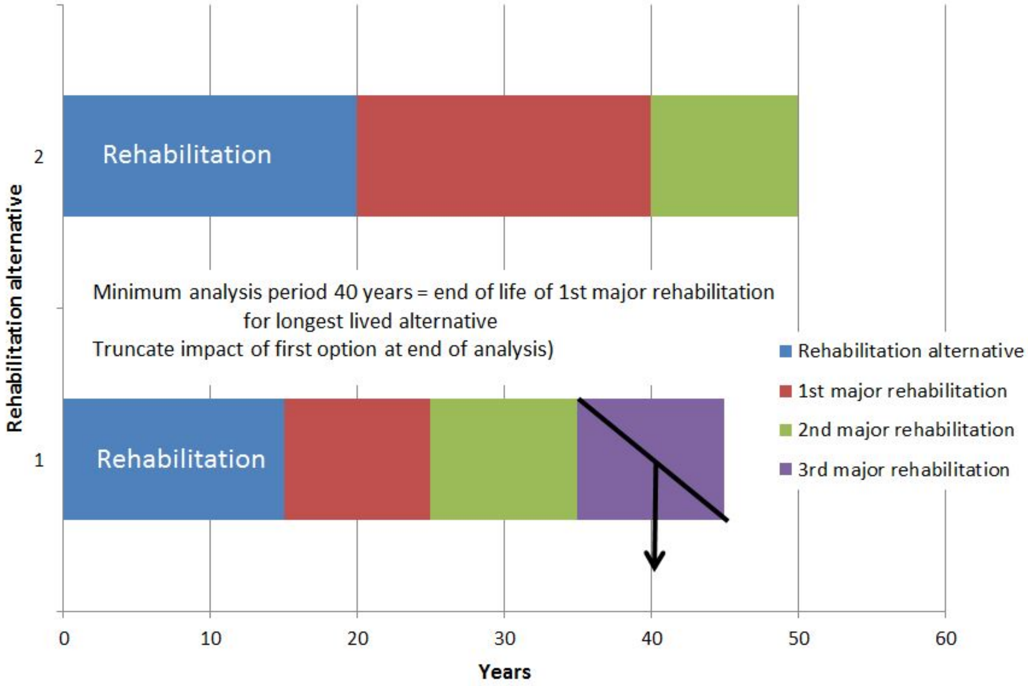
- When comparing a new pavement or reconstruction to a rehabilitation (see figure 5):
  - The analysis period should be the time through the life of at least the first subsequent major rehabilitation or reconstruction of the longest-lived alternative (typically the reconstruction).
  - The impacts of 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.



Note: the arrow indicates truncation after the life of the first major rehabilitation for the longest-lived alternative at 50 years.

Figure 5. Minimum Analysis Period Recommendation for Comparing a New Pavement or Reconstruction Alternative to a Rehabilitation Alternative

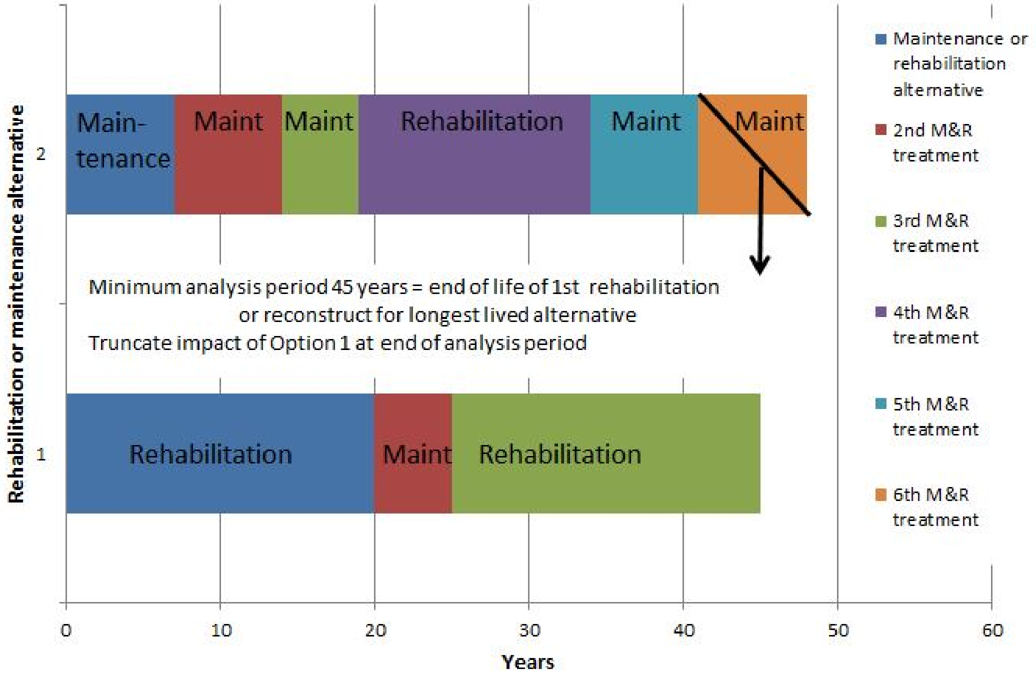
- When comparing two rehabilitation or maintenance treatments (see figure 6):
  - The minimum analysis period should be the time through the life of at least the next subsequent rehabilitation treatment of the longest-lived alternative if comparing rehabilitation treatments, and through the life of at 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.



Note: the arrow indicates truncation after the life of the first subsequent major rehabilitation for the longest-lived alternative at 40 years.

Figure 6. Minimum Analysis Period Recommendation for Comparing Two New Rehabilitation or Maintenance Alternatives

- When comparing a rehabilitation treatment to a maintenance treatment (see figure 7):
  - The analysis period should be the time through the life of at least the first subsequent major rehabilitation or reconstruction of the longest-lived alternative (typically the rehabilitation).
  - 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.



Note: the arrow indicates truncation after the life of the first subsequent major rehabilitation for the longest-lived alternative at 45 years.

Figure 7. Minimum Analysis Period Recommendation for Comparing a Rehabilitation Treatment and a Maintenance Treatment

After selection of the appropriate analysis period following the guidance given in the paragraphs 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 demonstrated for example in Wang et al. [47].

Where there is a large degree of uncertainty in future treatments, then sensitivity analysis should be included regarding 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. It is important to capture all the 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. [46]

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, and for pavement in terms of operations that it must carry regardless of the time period over which those occur [45].

The FAA pavement design practice requires using a 20-year design life, but recent research has found that airport pavements largely exceed this design life value, indicating that the FAA-recommended analysis period is too short [36, 48, and 49]. When one of the infrastructure systems or treatments in the LCA is extremely long lived, a maximum analysis period of 100 years is recommended, although it is expected that an analysis period this long will rarely if ever be needed.

Because the longest-lived system in the LCA, such as pavement handling low traffic volumes, will likely never receive a major rehabilitation or reconstruction and will receive only maintenance and preservation treatments, a minimum 35-year analysis period is recommended, following FHWA recommendations [50].

A good practice for civil infrastructure organizations with established LCCA guidance, if they essentially follow the guidance provided by U.S. DOT and this document, is to follow the same practices for selecting analysis periods for LCA. Definitions of maintenance, preservation, rehabilitation, or reconstruction should follow established LCCA practices for the agency.

Depending on the goal, the LCA study may consider less than the full life cycle of the pavement. For example, the goal may be to only consider the materials and construction stages, or only the use stage. In any pavement LCA study, careful consideration should be given to analysis periods that do not extend beyond the functional life of the next major rehabilitation or reconstruction. When these shorter periods occur, the reasons for not following the analysis period recommendations presented here should be explained in the goal and scope documentation.

3.4 DEFINE SYSTEM BOUNDARIES AND LIFE-CYCLE STAGES.

Typical life-cycle system boundaries include:

- Cradle-to-grave—a complete life cycle that includes the stages from extraction of raw material to incineration or burial of the product.

  For example, if the goal of the study is to determine the total life-cycle impacts for a concrete paved taxiway, then all the life-cycle stages are to be considered:

  - Material production (raw materials acquisition, transportation, manufacturing to ready to ship to construction site of all materials),

  - Construction (transportation of materials to the construction site, paving and compaction),

  - Use (albedo, aircraft tire pavement interaction, any heat and reflected energy due to pavement temperatures on aircraft and vehicle cooling requirements, edge/centerline lights),

  - M&R (milling, transportation of materials to and from construction site, paving and compaction), and

  - EOL (burial of the materials, recycling).

- Cradle-to-gate—a life cycle that includes the stages from extraction of raw material(s) to the production of the material(s).

  For example, the goal of a study is to determine the life-cycle environmental impacts for fences. This will include the materials stage (extraction of metal(s), paint production, oil extraction and refining, molding and manufacturing, paint application, and transportation of all the materials in each and every level within the materials stage) before the material is transported to the construction site.

- Cradle-to-lay—a life cycle that includes the stages from extraction of raw material to the pavement construction.

  For example, the goal of a study is to determine the life-cycle impacts of asphalt-paved aprons. This will include the materials stage (crude oil extraction, bitumen extraction in refinery, aggregate production at a quarry site, asphalt production, and transportation of all the materials) and the construction stage (transportation of materials to the construction site, paving, and compaction).

- Gate-to-gate—a life cycle that looks at partial materials stage, i.e., extraction of raw materials and their transportation to the production/manufacturing plant is not included in the scope.

  For example, the goal of a study is to determine the life-cycle impacts of creating mixtures from several ingredients such as paint, or hot mix asphalt (HMA), or concrete. This will have boundaries within the materials stage (i.e., transportation of cement and aggregates to the concrete plant and concrete production). If in this case the production of cement and aggregates going into the concrete mixtures were also considered, the analysis would become cradle-to-gate, which is discussed earlier. Similarly, the FAA may only be interested in the construction of a runway (transportation of materials to the construction site, paving, and compaction), which can also be considered to be a gate-to-gate analysis.

- Cradle-to-cradle—a life cycle in which the materials are recycled and used again and again in continuous cycles as the same product without losing their integrity or quality.

  For example, the goal of a study is to determine the life-cycle impacts for metallic signboards beside the taxiway. This will include stages such as materials (metal extraction, metal processing, and transportation of all the materials), construction and use (transportation of materials to the production plant, molding of the signboards, installation of the signboards beside the taxiways), M&R (cleaning the signboards, component replacement when required), and EOL (completely recycling the metal for the same purpose and project use, and transportation of the materials back to installation location and reuse).

Figure 8 shows an example used to define the life-cycle stages included in an EPD [51], and a similar figure can be used for documentation of the life-cycle stages included in any LCA.

To finalize the system boundaries and life-cycle stages, defining the unit processes, determining the cut-off criteria, and determining the sensitivity analysis criteria must be completed. Each item is discussed in sections 3.4.1, 3.4.2, and 3.4.3.

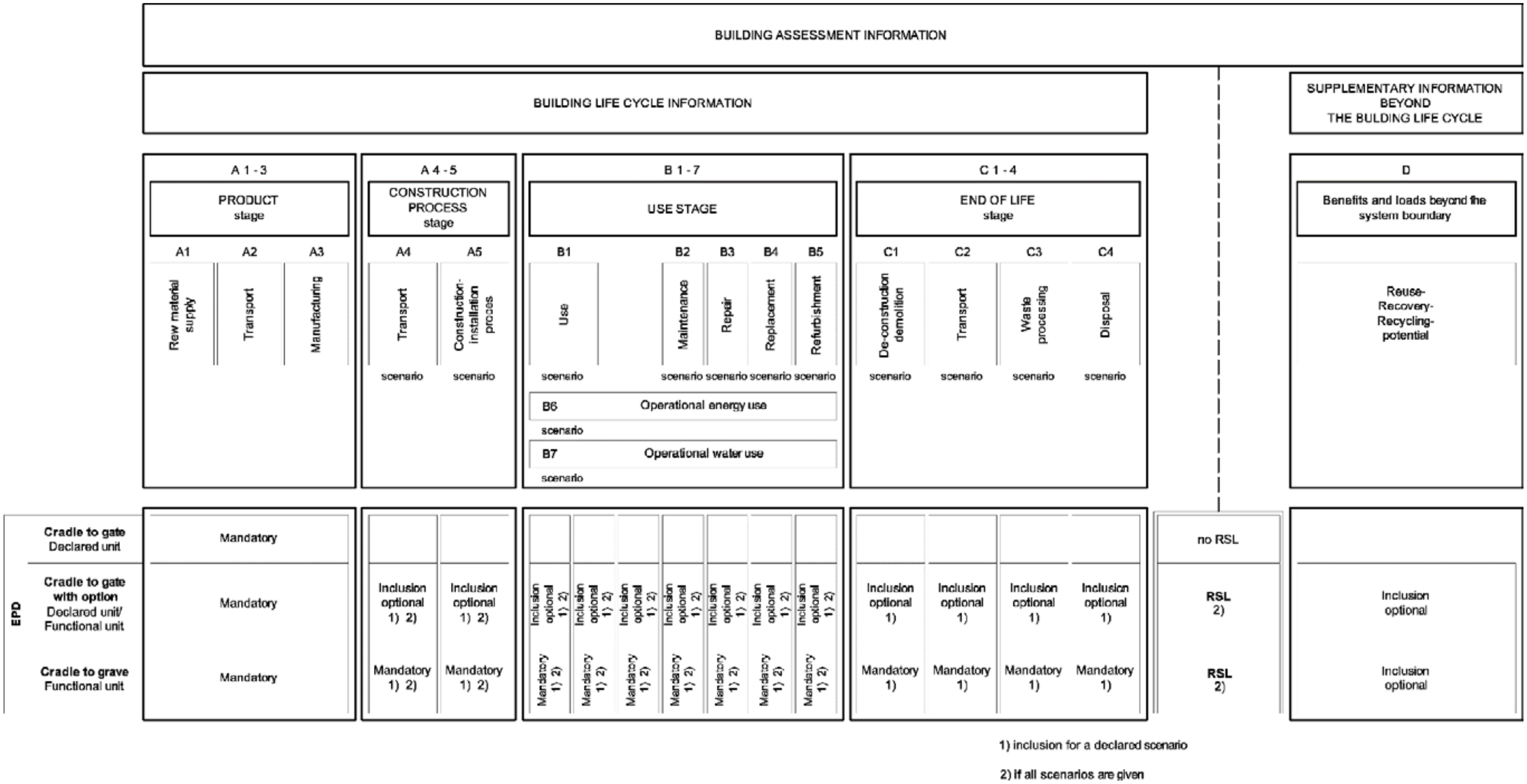


Figure 8. Defining Life-Cycle Stages Included in an LCA

3.4.1 Unit Processes.

Unit processes refer to all the processes that are part of the functional unit to be considered in the pavement LCA study. A system boundary is the set of criteria specifying which unit processes are part of the system being analyzed and which are not [5]. It is helpful to describe the system using a process flow diagram showing the unit processes and their interrelationships. Each of the unit processes included in the study should be defined in terms of [6]:

- 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

Figure 9 shows an example of a generic unit process. The raw materials and energy are the inputs to the process; and products, co-products, by-products, emissions, and wastes are the outputs of the process. Figure 10 shows a sample list of the elements of the processes in each stage that can be included in the 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 remains unchanged and are not part of the comparison, then those aspects of the structural design can be left outside the system boundary. Similar principles apply for exclusion of parts of the pavement system, depending on the goal of the study.

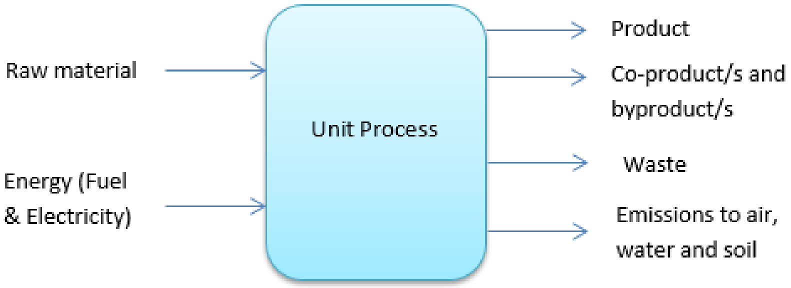


Figure 9. Unit Process of an LCA Showing Input and Output Flows

The following processes should be considered for inclusion in the stages shown in figure 10, depending upon the goal of the study [45]:

- Materials 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 section 5 for more guidance)

- Construction and M&R stages:

  - 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, 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 infrastructures built for the construction stage

- Use stage:

  - Additional fuel consumption by the traffic due to initial pavement condition and considering changes in the pavement condition over the analysis period. The pavement condition includes:

    - Roughness (Some calibrated models are available for land vehicles, but none are available for airfields.)

    - Texture (Some calibrated models are available for land vehicles, but none are available for airfields.)

    - Structural response (Models need to be specifically developed for aircraft and airside airport land vehicles; models are available and calibration is underway for highway vehicles, currently none for airfields.)

  - Effects of temperature changes in urban areas caused by the pavement (Modeling is currently being developed.)

  - Electricity used during the use stage 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 pavement during rainfall
  - Storm water runoff (Models are available, not typically applied yet to pavement LCA.)
- EOL stage
  - Reuse and recycling
  - Emissions and fuel use from demolition and hauling of debris
  - Hauling to a landfill
  - Leachate from landfilling (Availability of models is uncertain.)
  - Leachate from formerly bound materials now being used as unbound base (No models are available.)

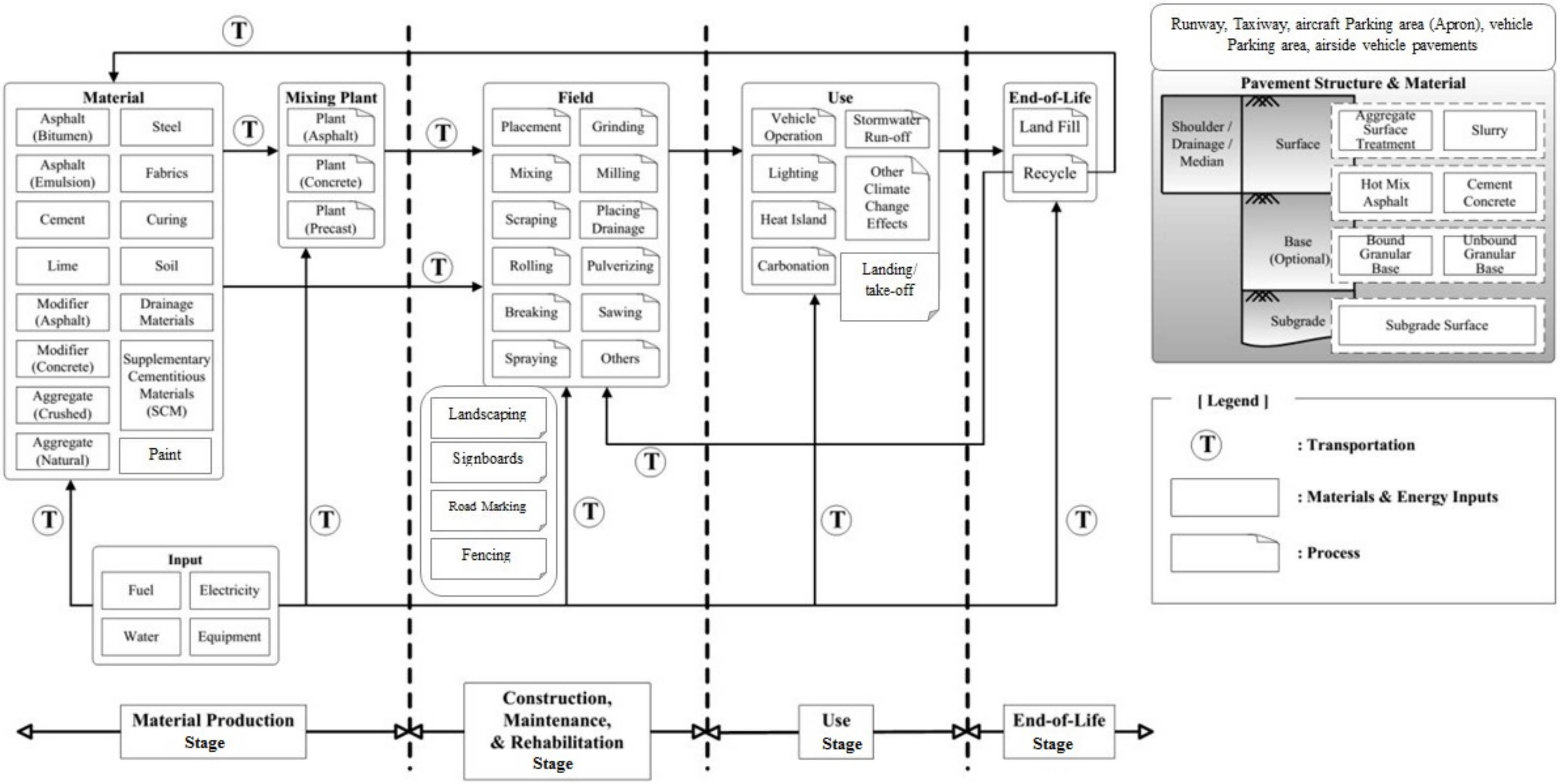


Figure 10. Processes Considered for Pavements (Modified and Expanded for Airfields)

3.4.2 System Boundaries and Cut-Off Criteria.

The system boundaries and life-cycle stages to be considered should be selected based on the goal of the study. According to ISO 14044 requirements [6], deletion of life-cycle stages, processes, or inputs or outputs for a given process should only occur if it does not significantly change the overall conclusions of the study. Omission of any life-cycle stages, processes, inputs, or outputs should be clearly stated, and the reasons and implications for the omission should be explained and justified.

Examples of processes considered in the different stages for pavement systems are shown in figure 10. For pavement systems, asphalt, cement, and aggregates are the major materials used in pavement structures that are considered in the materials stage. Other materials such as lime, geotextiles, polymers, steel reinforcements, and modifiers, etc., may also be used. The extraction of the materials, transportation of the materials to the material processing unit, processing, storage, and other processes up to the point when the material is available to be transported to the construction site are considered in this stage. The manufacture and maintenance of the material processing equipment is in this stage and may be included in the system boundary.

The construction stage mostly includes the transport of materials to the construction site, laying, and compaction of different pavement layers. The manufacture and maintenance of the equipment used for the construction of pavements also falls under this stage, and may be considered within the system boundary.

Pavement interaction with vehicles and aircraft can cause excess fuel consumption and additional maintenance for them. This includes the airside pavement/vehicle interaction, which includes the additional operation and maintenance effects caused by the pavement condition compared with perfect pavement. Aircraft and freight tugs will have a large impact over the life cycle because of their frequent use. The aircraft/pavement interaction that occurs when the aircraft takes off or lands on the runway and when it taxis on taxiways from aprons to the runway and vice versa are other factors to consider. Other use stage effects to consider include emissions to storm water, storm water handling, interaction of the pavement with requirements for lighting and pavement markings, and effects of pavement on air and pavement temperatures at the airfield, which can influence aircraft, vehicle, and building heating and cooling requirements.

M&R need to be considered in the pavement life cycle. Less durable materials and structures and lack of preventative maintenance, such as resealing joints for concrete pavements and crack sealing for asphalt and concrete pavements, will require more frequent M&R and possible replacement in the life cycle. Material extraction and construction impacts used in maintenance are also included in M&R. The potential options available at the end of the pavement service life are milling followed by disposal in landfills, in-place processing for reuse in the same pavement, or material removal for off-site processing into new pavement material. Reclaimed materials from external processes may also be included in the pavement, such as building demolition, reclaimed concrete from plant waste, recycled tires, fly ash, and steel slag. One M&R strategy employed on airfields that does not occur on roadways is brooming, which is a critical operation performed at airports to reduce foreign object debris (FOD) and protect aircraft and passengers.

Drainage components that can be included in the LCA are ditches, bioswales, culverts, detention basins, trench drains, pipe underdrains, storm sewers, temporary drainage during construction, and any subcomponents contained within these systems (such as headwalls as a subcomponent of culverts). The life cycle for drainage will include the same stages as pavements with the exception that the use stage in this case will include runoff infiltration, inflow, and treatment.

For all other airfield systems, including fences, signboards, sign markings, and pavement lighting, the materials stage will include the extraction of the raw materials, transportation, and construction. The use stage will include the production of the products mentioned earlier and any effect that continues over time, such as lighting. The M&R stage will include product maintenance, such as fixing light bulbs and readjusting fences; and the EOL stage will include the waste management of the products.

The last item that may need consideration in an airfield LCA is landscaping. Landscaping will consider any processes needed to maintain the land within the fence line. Examples of these activities include sprinkler system operation in the terminal area, lawn mowing, and use of fertilizers, herbicides, and pesticides.

Excluding life-cycle stages could lead to conclusions with important, negative, unintended consequences. For example, a material may have a low environmental impact from its production, but it may not be durable, which could lead to frequent replacements; or it may cause roughness, which could affect 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 materials 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, 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. In a single-system attributional study for a pavement structure, all elements should be included. In a comparative study where certain elements are exactly the same throughout the analysis period and make no difference to the inputs or outcomes, they can be excluded, and this should be documented; however, the results are also not comprehensive in terms of total impact, and this too should be documented.

Cut-off criteria specify the criteria for excluding unit processes, or inputs or outputs, from unit processes. This is considered acceptable practice and is usually done to reduce the effort of creating data inventories by not requiring inventories for flows that are not expected to affect decision-making. However, this creates a dilemma in that preliminary inventory data must be collected and analyzed to determine the expected impacts and whether the cut-off criteria were met.

Cut-off 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 5% for all cut-off flows is the recommended threshold for each of the criteria (mass balance, energy balance, and environmental aggregated flows and impacts). The following are definitions of mass, energy, and environmental impact criteria [6]:

- Mass: an appropriate decision, when using mass as a criterion, would require the inclusion in the study of all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modeled.

- Energy: similarly, an appropriate decision, when using energy as a criterion, would require the inclusion in the study of those inputs that cumulatively contribute more than a defined percentage of the product system's energy inputs. The various forms of energy (primary, secondary, renewable, nonrenewable, used as fuel, and stored in a material) can be considered for cut-off and truncation, although ISO and the European Committee for Standardization (CEN) standards do not differentiate what energy types to consider. In general, primary energy demand (PED) is used as the energy cut-off criteria.

- Environmental significance: decisions on cut-off criteria should be made to include inputs that are specially selected because of environmental relevance although they do not meet the other cut-off criteria.

While inventories are available for many pavement materials, they are not available for a number of materials used in small mass quantities that potentially have large energy and/or 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 unknown, which makes it difficult to create a new inventory even when one does not exist. At this time, the following are possible approaches, suggested in order from short- to longer-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 an estimate of 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 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 and/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 can be aided by use of technology such as Fourier Transform Infrared Spectroscopy (FTIR), which can identify many known chemicals and is increasingly available in pavement materials laboratories.

3. Make EPDs a requirement for all materials used in pavements. The Netherlands, Norway, and Sweden are examples of countries that require EPDs in a procurement process. In 2019, pilot projects to be conducted in California will require contractors to submit EPDs with their project bids. Submission of EPDs is expected to be mandatory in California by 2021.

The cut-off criteria used in a pavement LCA study should be established based on accepted standards such as EN 15804 [12] or ISO 14044 [6], and the assumptions on which the cut-off criteria are established should be clearly described in the LCA scoping. The final report should also assess and describe what effect the selected cut-off criteria have had on the outcome of the study; the assessment and description should be part of the sensitivity analysis.

Several types of cut-off criteria are used in LCA practice to decide which processes and inputs and outputs are to be included in the assessment; these include mass balance, energy balance, and environmental significance. All three criteria should be considered for cut-off in pavement LCA. Identification of inputs based on any two or three criteria alone may result in important inputs with significant effects on the third criterion being omitted from the study. 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 large mass contributions.

Results from studies used to make comparative assertions intended to be disclosed to the public should include a final sensitivity analysis of the inputs and outputs. The sensitivity analysis should consider the mass, energy, and environmental significance criteria. For each criterion the analysis should show that all the processes and inputs/outputs included cumulatively amount to more than at least 95% of the total contributions [6]. This cut-off threshold can be difficult to meet considering the uncertainty of pavement and other airfield civil infrastructure inventories at this time.

3.4.3 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 [6]. A process and the 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 scope definition. Application of the cut-off criteria can only be done once inventory data begin to be collected; and as inventory data are collected and impact analysis begins (defined in section 5), the system boundaries may need to be adjusted based on the results of sensitivity analysis and application of the cut-off criteria.

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

- Functional unit
- Analysis period
- Processes and inputs and outputs for individual processes in the LCI

- Life-cycle stages
- Traffic considerations in the use stage
- Future rehabilitation and maintenance treatment types and schedule based on variability of performance and alternative future decisions
- Fleet composition
    - Speed distributions that may affect pavement/vehicle and pavement/aircraft interactions
    - Traffic flow changes (changes in aircraft operations, and/or support vehicle operations)
    - Improvement of vehicle technology and emissions standards
- Allocation methods (defined in sections 3.5 and 5)

3.5 DETERMINE ALLOCATION PROCEDURES.

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

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

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 [6]. ISO recommends that allocation be avoided wherever possible; but where it is unavoidable, it is important that the input or output flows be partitioned in a practical way that reflects their actual relationships. There are a number of situations in pavement and airfield 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 (SCMs) in hydraulic cement concrete (HCC) where the environmental benefits of replacing some of the portland cement concrete (PCC) can be attributed to the concrete or to the upstream production of the SCMs, but should not be attributed to both.
- The use of recycled materials where allocation is needed to account for the upstream processes outside of the pavement system or the pavement processes as well. A similar situation can be applied to any materials coming into pavement from industries that are primarily focused on non-pavement products.
- Environmental effects of recycling existing pavement materials into new pavement materials where the impacts can be attributed to the new material or the original material.

- Use of recycled metals in pavement load transfer devices and lighting fixtures.

- Any product's manufacturing stage where co-products and/or by-products are also produced.

The main points of the allocation procedures outlined in ISO 14044 are summarized as guidance for pavement LCA practitioners in this document; more details are provided in the ISO document [6]. 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.

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

- 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.

This consensus is based on presentations and discussions at the 2012 Nantes conference on LCA for civil infrastructure [15] and the 2014 International Symposium on Pavement LCA held in California [16].

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

Double-counting (see section 4) is not permitted in accordance with the ISO standards, and presents a major problem in the transparency and use of LCA studies to effectively determine environmental burdens. Currently, there is no authority in the U.S. or any other part of the world that can determine the appropriate approach when double-counting occurs 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 infrastructure materials processes, allocation should typically be included in the sensitivity analysis for pavement LCA studies as is discussed in section 4. The sensitivity analysis for allocation methods should be documented in the scoping of the LCA study.

3.6 SELECT AGGREGATED FLOW, IMPACT CATEGORIES, AND IMPACT CATEGORY INDICATORS.

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 [6]. The purpose of LCIA is to better understand the environmental significance of the 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 [6]:

- 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 stage 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.

Selection of impact indicators includes decisions regarding whether midpoint indicators or endpoint indicators will be used. Guidance regarding specific impact category indicators for pavement and other LCA in the U.S. is presented in section 5.

The recommended steps in selecting impact categories and indicators are as follows:

1. Review the goal to determine if the full set of impact category indicators is useful for achieving it; and if not, determine 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 that could be relevant to the sponsors or other stakeholders in the project (those directly involved or those affected at the location) other than those that directly support the stated goal, 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 the impact category indicators (further information is presented in section 5).

4. Determine whether to conduct normalization, and if so how normalization (often by weighting the indicators) will be conducted to support the goal of the study and the needs of stakeholders. In accordance with ISO 14044 [6], 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 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. See section 5 for further details.

Impact category indicator results can be normalized, grouped, and/or weighted, but the decision regarding how to handle those indicators needs to be identified in the scoping of the study. Section 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, which reduces the present value of costs that occur later in the analysis period. There is no equivalent to a discount rate for emissions or energy use that the scientific LCA community has agreed upon, and emissions should be treated as having equal impact throughout the life cycle, except where dynamic characterization factors are available that account for the changing effect of an emission over time.

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, and can range from narrowly focusing 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 depletion of material resources. Work by Laurent et al. [52] 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 burning of carbon-based fuels are less likely to be tied to those two commonly selected indicators.

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 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.

Impacts indicators occurring during the analysis period, which 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 as opposed to national or international averages. While global warming and ozone depletion have global impacts independent of the site of the emissions, the other impacts listed often have regional and local impacts with strong dependency on emission site [53]. It should be noted that some of the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (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 [54 and 55].

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 but at the beginning of the analysis period.

3.7 DEFINE INTERPRETATION PROCESS.

Life-cycle interpretation is the phase of LCA 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 to reach conclusions and recommendations [6]. 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 [6] (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 including, in particular, data quality requirements, predefined assumptions and values, methodological and study limitations, and application-oriented requirements.

4. If the conclusions are consistent, report them as full conclusions; otherwise, return to previous steps 1, 2, or 3, as appropriate.

Comparisons between products should be interpreted on an impact-category–by–impact-category basis and not based on averaging or other calculation 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 required 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.

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

3.8 DOCUMENT ASSUMPTIONS.

The assumptions of the study developed through the previous six major steps in the goal and scope development process should be documented as a part of the scoping of the LCA study. These should include documentation of the items previously discussed in this section, as well as any other assumptions that will be used during any of the subsequent stages of the study (inventory, impact assessment, and interpretation).

The reasons for the assumptions and their expected effects on the results should also be documented, including any changes in assumptions made after the scope and goal have been initiated. Some assumptions in the scoping phase can include reasons for the 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.

3.9 DOCUMENT LIMITATIONS.

The study limitations 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 section, as well as any limitations that will be imposed during the subsequent stages of the study (inventory, impact assessment, and interpretation). The reasons for the limitations and their expected effects on the results should also be documented.

The following items should be considered specifically, as a minimum, when documenting the limitations of the study in the goal and scope document:

- 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

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, 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).

3.10 DEFINE DATA REQUIREMENTS.

The scoping of the LCA study should describe the requirements for data used in the inventory and impact assessment phases to be able to answer the questions posed by the goal and 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 stage 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:

- Primary or secondary data
- Average data or specific data
- 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 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 section 4.

Data for a project-level analysis should be specific to the project and, where possible, should include primary data from similar recent projects. Data for facility-level analysis can include a factorial representing the range of systems and conditions across the facility, or if they are available, facility-level databases for the entire facility should be used. Data for policy analysis should consider a factorial of pavements and conditions for which the policy will be applied.

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

3.11 DEFINE DATA QUALITY REQUIREMENTS.

Data quality requirements should be documented in the scoping of the LCA study. Any limitations on data and data quality should be identified and documented.

The following are items to consider when determining data quality requirements:

- 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.

According to ISO 14044, data quality is defined as "characteristics of data that relate to their ability to satisfy stated requirements" [6]. The data quality requirements are therefore dependent on the goal of the study. Data quality requirements should specifically address the following items (based on ISO 14044 [6]), 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

- Precision: measure of the variability of the data values for each data expressed (e.g., variance)

- Completeness: percentage of flow that is measured or estimated

- Representativeness: 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: 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)

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.

Criteria for assessing data quality are presented in section 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 is often sought as a replacement. Similarly if the preliminary sensitivity analysis indicates that there is little sensitivity of the indicators to the quality of certain data elements, then the level of data quality for those elements can be lower.

Figure 11 presents a simple flowchart for determining data requirements during the scoping of the LCA, illustrates the movement from the goal and functional unit of the study to the indicators and to the data needs, and finally to the data quality to successfully achieve the study goal [12]. More information on data requirements is presented in section 4.

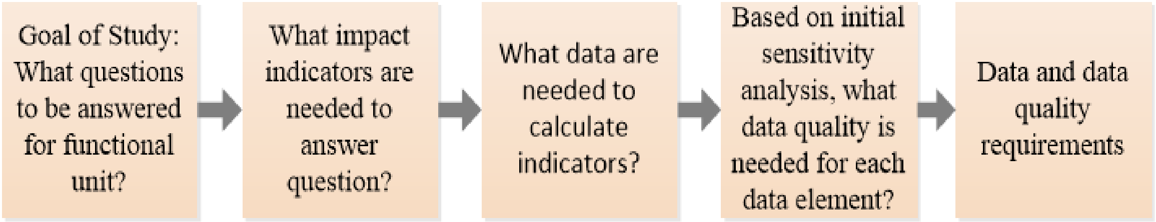


Figure 11. Determining Data Requirements During Scoping of the LCA

<u>3.12 DETERMINE CRITICAL REVIEW PROCESS</u>.

LCA studies require a decision regarding critical review that should be determined during the scoping of the study. The critical review evaluates how the LCA study is conducted and whether it addresses the stated goals. It also evaluates the scientific rigor as well as the data and methodology used throughout the study.

The steps in the critical review determination process are [6]:

- 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 scope of critical review and mandate given to the reviewers.

- Who will be selected to conduct the review based on the expertise required, and who will chair the review committee?

- Process of critical review, including stages of review.

A critical review is likely not needed if the study results are to be informally used for internal purposes, such as internal benchmarking for efficiency improvement at a pavement materials plant or 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.

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 if it is a comparative study. External reviewers should be used for comparative studies that will be published for other than internal 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.

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

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 [6], including:

- The methods used to perform 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.

Details regarding critical review are included in section 7.

3.13 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 section
- Documentation of changes in the scoping and assumptions that occurred during execution of the study
- Transparency documentation

The report format should follow ISO 14044 [6] 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 section 7.

3.14 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. 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 (see figure 3) will typically be reduced in scope, which will simplify the work in the succeeding steps. The outline of the scoping document should follow the goal and scope flowchart developed for the study.

4. THE LCI ANALYSIS.

4.1 THE LCI.

ISO 14040 [5] defines LCI as “the phase of LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.” These inputs and outputs are called “flows.” The steps involved in creating an LCI are defining the flows into and out of the processes that are within the system boundaries, and collecting the necessary data to quantify the relevant input and output flows. It is important to note that whatever data collection procedures are selected may change during the inventory analysis as more information is gathered and further limitations on data availability, quality, and completeness are realized. There may also be circumstances that require returning to a previous step and redefining the goal and scope if it is determined that the current goal and scope cannot be met because of limitations in the LCI phase. Figure 12 shows the inventory analysis process in accordance with ISO 14044 [6].

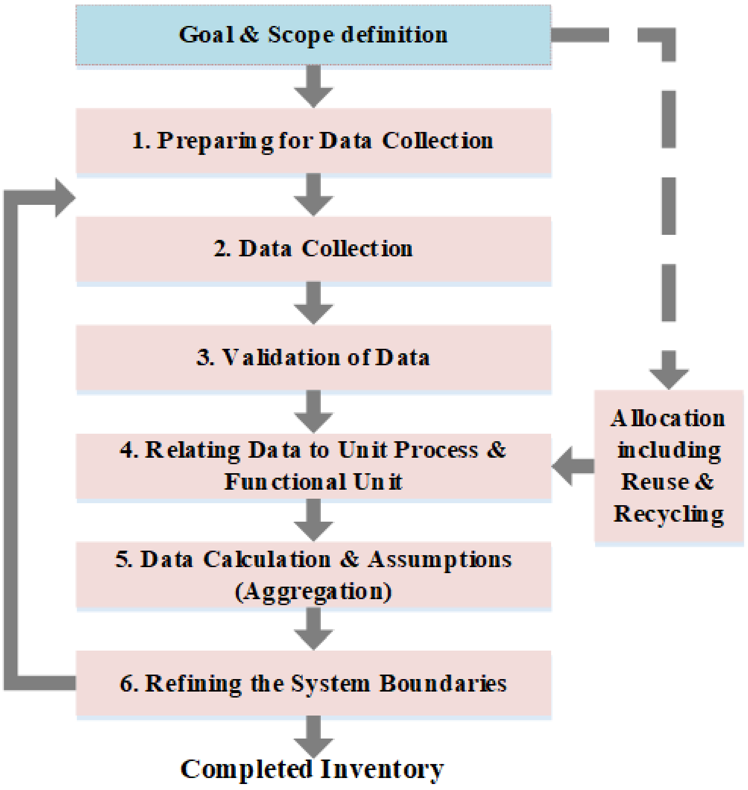


Figure 12. Key LCI Procedures Recommended for Each Unit Process

According to ISO 14044 [6], these are the major types of flows for which data collection is needed:

- Energy inputs, raw material inputs, and other physical inputs

  Energy can come from both renewable and nonrenewable resources. Renewable resources include solar, wind, biomass, geothermal, etc., whereas nonrenewable resources mainly include hydrocarbons (petroleum, natural gas, coal). Energy inputs occur through all life cycle stages for airfield infrastructure LCA, such as the energy involved in mining and transporting petroleum, limestone and aggregates, and metals; processing these materials; transportation of materials, operating equipment such as pavers and compactors at the job site, additional energy used by vehicles, buildings and lighting caused by the pavement, and any processing and transport at the EOL. Raw material inputs are the materials needed to produce a product.

- Products, co-products, and waste

  The product is what is produced by a given process, such as a material like HMA or concrete, wiring, drainage pipes, or a completed infrastructure system (e.g., a drainage system, a lighting system, or a pavement structure). Co-products are produced when there are multiple products resulting from a given process, which mostly occurs for materials production. Asphalt binder is an example of a co-product since the petroleum-refining sector also produces gasoline, diesel, and other fuels as well as lubricants from the refining process. Environmental impacts need to be allocated among the co-products as described later in this document. Waste is an output of a system that cannot be used as an input for another process or as a final product and that has no economic value other than what could be created from it by additional processing and transportation to allow its use in a pavement or other airfield feature. For example, the fly ash produced by burning coal is generally considered a waste since it is land filled unless it is processed and transported for use as a SCM.

- Emissions to air, discharges to soil and water

  Emissions fall into two categories, direct and indirect. Direct emissions are produced from the product itself. Indirect emissions are a result of other inputs into the process that do not directly come from the product, such as the carbon dioxide (CO_2) that comes from burning fuel to heat limestone and other rocks to make clinker for cement or the emissions that come from burning natural gas or fuel oil at an asphalt mixing plant to heat asphalt binder. Emissions can be gases, solids, or liquids.

LCI analysis seeks to identify and quantify all the unit processes that are within the boundaries of the defined system. Ideally, data should be collected for each and every unit process (see figure 10) since these individual processes work as building blocks for the complete process, activity, and system within an LCA.

4.2 DATA COLLECTION PREPARATION AND PLANNING.

Data collection preparation and planning involves the collecting and modeling of the inventory data within the system boundaries of the study. The data in the inventory is classified as either primary data (also known as specific or foreground data) or secondary data (also known as generic or background data).

Primary data are those that are specific to the processes in the LCA study, while secondary data are those that have been collected for another purpose/project but can also be used for the current study. Examples of primary data include measurement of inputs, such as energy use and raw materials, and measurement of outputs, including the product, co-products, waste, and emissions. Examples of secondary data include averaged data collected from a number of similar processes in a region, such as a number of asphalt or concrete mixing plants. Secondary data also includes data collected elsewhere and then adjusted to account for differences between the processes that were measured and the similar but different processes in the current LCA study. Secondary data can also include data from models of processes using inputs specific to the processes in the current LCA study. Use of primary data is preferable. It is also possible to combine primary and secondary data, depending upon what is available.

4.2.1 Preparation for Data Collection.

According to ISO 14044 [6], the first step of the inventory analysis is to prepare a data collection plan that will outline the specific procedures to follow for gathering required inventory data. The plan will specify which data will be primary and which will be secondary, a distinction that will have to be made after a quality review of the available data. It is likely that this plan may need to be adjusted as the data collection process proceeds. An example data collection plan is presented in table 6.

In this brief example of data planning (table 6), material production, transportation, and placement and compaction of a granular base layer are considered. For two of the four processes, primary and secondary data could be selected. As noted earlier, primary data is always preferable (as in the case of aggregate production), but at times the only option is to select data from secondary sources. As table 6 also shows—for transportation and construction—there may be more than one option. The data most relevant to the project should be selected, and where possible, secondary data should be adjusted for local conditions to make them more representative of the processes used in the current study. For example, the electricity used to operate crushing, belt transportation, and lighting in the quarry can be adjusted to reflect the sources of electricity in the grid that the quarry draws from.

Table 6. Data Collection Planning

Stage	Products	Processes	Data Type and Data Source	
			Primary Data	Secondary Data
Construction (Base Layer)	Aggregate	Production	Quarry site "A" located in "X" keeps ongoing records of the total electricity and fuel consumption data to produce 100 tons of aggregate every year.	Quarry site "A" located in "X" has published average energy consumption data to produce 100 tons of aggregate over the last four years.
		Transportation and storage in the quarry	Data unavailable	Average energy consumption values for belts and trucks available in the literature for quarry sites located near location "X."
	Transportation	From quarry site to construction	Data unavailable	Fuel consumption data for a specific type of truck typically used in the region available from commercial databases. OR Fuel consumption averages available in the literature for some other similar material transport vehicles.
	Construction	Placement and compaction	A contractor has fuel consumption and other consumable material data for typical graders and compactors used in the region and the amount of operation needed to meet specified compaction. OR Data on fuel consumption for specific graders and compactors used locally is available in a commercial database.	Fuel consumption averages per horsepower of different types of graders and compactors are available in the literature but not for the compactors used in location "X," and data on the horsepower of engines of typical local graders and compactors are available.

4.2.2 Data Collection.

When possible, data needs to be collected for every unit process included within the system boundary. These data are used to quantify the inputs and outputs of a process. Data can be measured, calculated, or estimated, depending on the limitations of the collection process. If primary data are unavailable, data modeling can be done, (i.e., other available data can be collected or calculated and then adjusted to get acceptable and rational results). Data should be collected first and then transformed to meet the LCA study's data requirements.

As mentioned, primary data is the preferred type; but collecting it can be time-consuming and expensive, so obtaining it may not be possible. The next best option is to collect primary data on the process and model the emissions associated with the process and those inputs. As an example, assume the amount of diesel fuel consumed to transport material from one location to another is 100 gallons. Since each gallon of diesel consumed produces 11.9 kg of CO_2, the total CO_2 emissions produced from the example project will be $11.9 \times 100 = 1190$ kg.

Measures need to be taken to ensure that the product systems being modeled are consistent. The following is a list of measures given by ISO 14044 [6] to ensure consistency:

- Draw general process diagrams which outline all the unit processes to be modeled as well as their interrelationships.
- Describe each unit process in detail with respect to factors influencing inputs and outputs.
- List the flows and relevant data for operating conditions associated with each unit process.
- Develop a list that specifies the units used.
- Describe the data collection and calculation techniques needed for all data.
- Provide instructions to clearly document any special cases, irregularities or other items associated with the data provided.

All the processes that occur before a given process are called upstream processes and those that occur after the given process are called downstream processes.

Figure 13 shows an example of a process diagram that outlines the unit processes and their interrelations upstream of the production stage of crushed stone [56]. To get the total energy consumed and emissions from production of 1 ton of aggregates, there are number of upstream unit processes that need to be considered and modeled. Electricity, diesel, residual oil, gasoline, and/or lignite coal are required as energy inputs to produce the crushed stones/aggregates. However, each energy input has its own upstream environmental declarations or impacts that are linked to the production of that energy resource. If modeling is needed for the processes further upstream to meet the system boundaries of the goal and scope of the LCA study, the modeling could also include the allocated energy and emissions from the manufacture or construction of the upstream infrastructure, in addition to the consumable material used during production. Upstream infrastructure can include any refineries, dams, nuclear plants, etc. The upstream processes that must be considered in an LCA study are defined by the study’s scope and cut-off criteria (section 3.4.2) and by the availability of data. Processes that occurred after production of the crushed stone, such as its transport and mixing in of PCC or asphalt concrete, would be considered downstream processes.

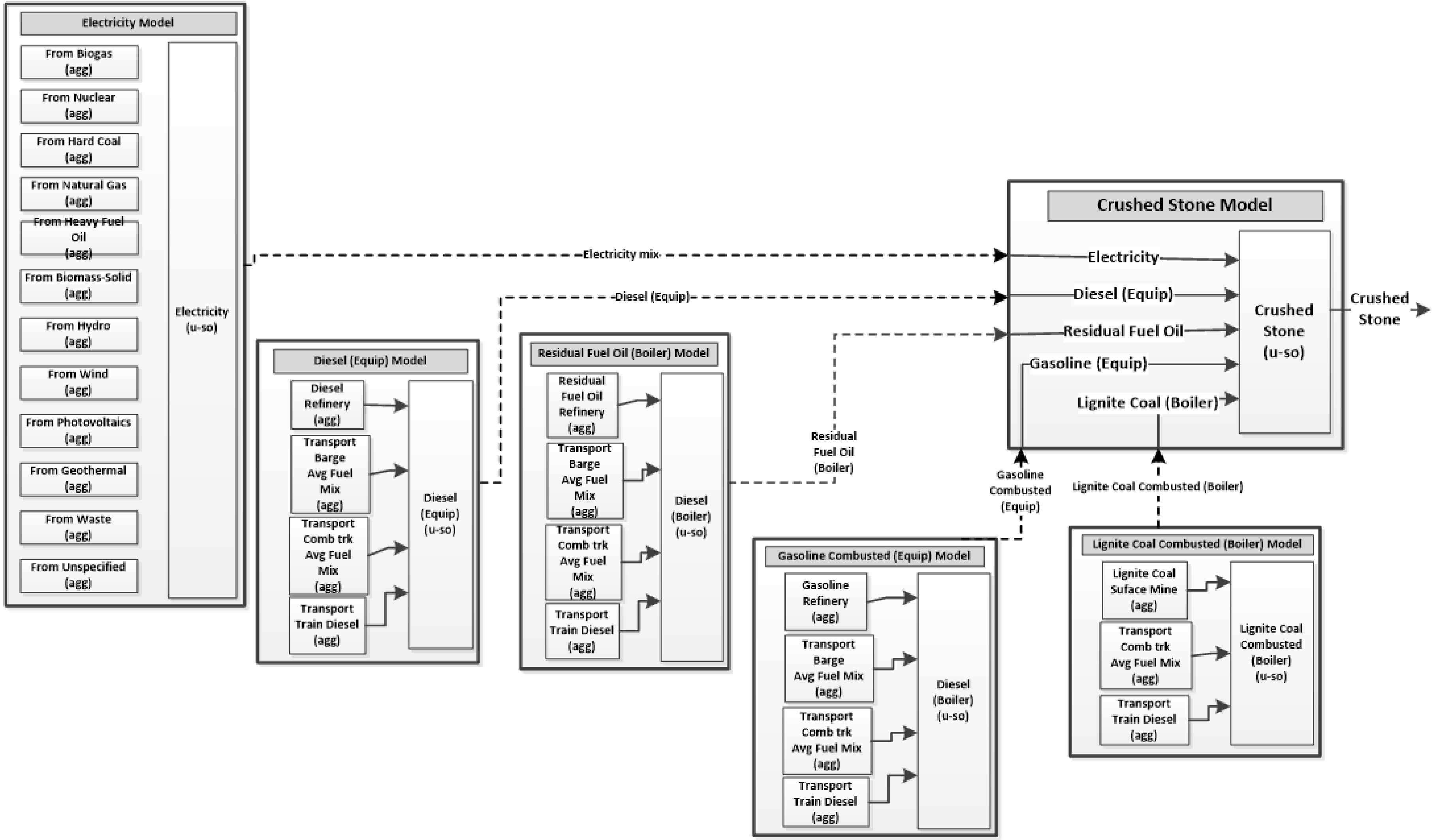


Figure 13. Crushed Stone Upstream Processes

Assuming that none of the previously mentioned options for primary data or modeling using primary data for inputs to the model are available for a given process, a representative value from the literature can be used with proper documentation and assessment of whether it meets the data quality requirements of the goal and scope. For all data that are relevant to the conclusions, it is necessary to specify the details of the collection process, the time that the data was collected, and any relevant information about the quality of the data. More information about data quality review and reporting is included in section 4.7.

When using modeling, plant-specific input data are always better than industry averages, although both are acceptable based on what is available. Data from public sources and literature can also be considered usable if they meet the quality requirements identified in the goal and scope. Table 7 lists different data types, measurements, and some common issues.

Data collection can become more difficult as a study becomes more complex or the level of detail needed to meet the goal and scope increases (figure 14) [57]. At the facility-level (stage at which new projects are to be decided) and conceptual planning stages less information is needed regarding what and how things will be done, fewer resources are available to perform the LCA, and less information is available regarding the functional unit. As a result, secondary data from existing completed projects are typically used. Conversely, for a project-level LCA, the project scope and functional unit is well-defined and more specific data becomes easier to obtain; therefore, either primary data or a combination of primary and secondary data are typically used.

For example, if a decision is to be made to build a new taxiway (facility level), available data averages (secondary data) [58 and 59] will most likely be used—based on previously completed projects and experience—because nothing certain is known this early in the project-planning stage. Once the project is selected or decided upon, it will go through iterative design stages with each stage introducing more available data from the conceptual design and comparison of alternatives to the final design. As the level of detail regarding the design progresses, it will be easier to obtain primary data since it will be clearer what materials types and quantities and processes will be used and from whom the materials and services will be procured.

Table 7. Data Types, Measurements, and Issues

Data Type	Measurable	Issues
Plant-specific	Directly measured from the source using measuring equipment. Data is also associated with a specific geographic location or production plant. Examples: • Emissions measured from the smokestack of a material production plant or a power plant • Emissions directly measured from an on-board emission measurement device hooked up to the tailpipe of vehicles • Fuel meter connected in between the fuel tank and burner that measures the exact fuel used • Electricity meter connected to the aggregate conveying belt in an asphalt/concrete plant to determine accurate electricity consumption These measurements can be classified as primary data.	• The measurements are expensive. • Permissions are required to install extra measuring equipment. • Long-term measurements are required to get good results. • Frequent maintenance is required for extra equipment.
Models	Models define how certain variables are related/connected to each other and how they can be processed within a system. Inputs and outputs are identified and calculated. Example: • Output: Total energy consumption in J from transporting material from A to B Inputs required: Transport vehicle's fuel efficiency (E) in liter/km, energy density of fuel (F) in J/liter and total distance traveled from A to B (D) in km. The model that gives the required output: $(E \times F \times D)$ Primary data can be used to calculate or create secondary data.	• The results could be wrong possibly due to incomplete information. • Sometimes lots of assumptions are involved.
Industry Averages	This could be considered as a benchmark in a material production industry. Examples: • Coal-fired electric power plants accounted for 95.5% of West Virginia's net electricity generation in 2014, whereas, California hardly generated electricity from coal that year. The industry average (electricity generation) from coal in the U.S. was considered as around 33% [58]. So an industry average may be used in case information on electricity generation from coal is unknown in a certain state. • Industry averages of concrete [59] are mostly used due to unavailable production data on concrete in most U.S. states. It is mainly a combination of primary and secondary data that is plant specific and calculated from data models (i.e., averages of data in a selected industry).	• The results could be considered biased. • Not representative of actual condition. • Good but not the best. • The closest acceptable value could be far from reality.

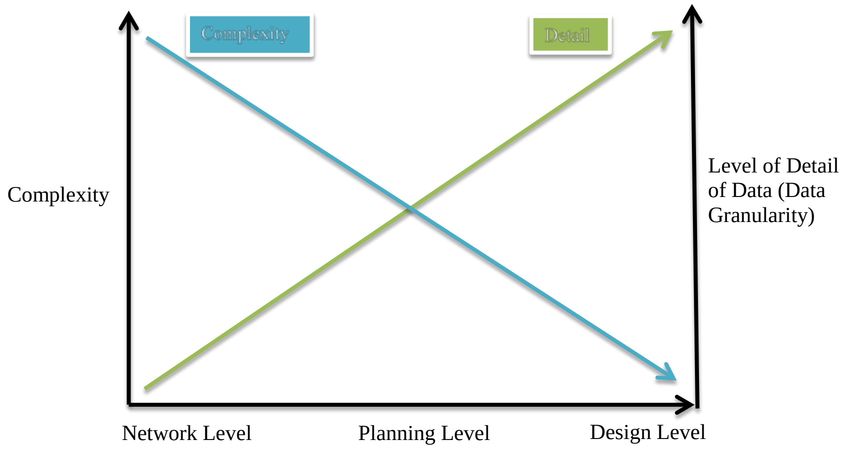


Figure 14. Complexity of Studies and Data Availability From Facility (Network)-Level to Design-Level

A description of each unit process, including definitions of co-products, waste products, and allocation, is necessary to avoid double-counting, which can cause either overestimation or underestimation of inputs and outputs. For example, overestimation would occur if a specific concrete mix was used and the production energy was reported, but the upstream processes were unknown and not reported. If an additive such as a water reducer is to be used, and it is added to the flows of the concrete mix, but the additive was already assumed in the reported value of the concrete mix, then this would result in double-counting resulting in an overestimation. On the other hand, double-counting leading to underestimation would occur in a situation where a supplier of slag that was used for blending into PCC reported an emission value for the slag that already included a downstream reduction in the use of cement, and the unit process for the blended cement in the current study were to use that slag emissions value, thereby directly reducing the amount of emissions from replacement of PCC with slag.

4.2.3 Validation.

A validation check must be performed on all data collected. The validation check involves confirming that the data fulfills the data quality requirements defined in the goal and scope (see section 3.11). There are several steps that can be taken for validation. Since a unit process follows the laws of conservation of mass and energy, the first step is to ensure that the inflows are equal to the outflows for mass and energy by performing a mass balance and energy balance check.

For example, for a mass balance check of the diesel fuel combusted to heat aggregates when mixing asphalt and aggregate to make HMA, 1 liter of diesel consists of 720 g of carbon, requiring 1920 g of oxygen for complete combustion. Therefore, if 1 liter of diesel is completely combusted to heat 1 kg of aggregates, 2640 g of CO_2 will be produced.

Another suggested and very useful, but not mandatory, step is to locate a similar study and compare the LCI results of comparable unit processes, while accounting for differences in the definitions of the unit processes being compared. An example benchmarking study is shown in Harvey et al. [60].

4.2.4 Relating Unit Process Data and Functional Unit.

The appropriate flows that relate unit processes to the functional unit need to be determined. All input and output flows relate back to this reference flow.

Data aggregation is a process in which the upstream information is gathered, summed, and presented as a single value (summary). Data can only be aggregated if the flows or impacts relate to equivalent substances or environmental impacts calculated in the same way, respectively, and have same units.

4.2.5 Data Calculations and Assumptions.

All calculation procedures should be explained in detail, along with any assumptions. The stated calculation procedures and assumptions need to be consistently followed throughout the study.

If it is stated that the energy in the materials of an asphalt mix will be calculated based on the job mix formula and values for the materials found in the literature prior to calculation of the additional energy input to mix them, then that procedure needs to be followed throughout the study. For example, if the functional unit is 1 ton of HMA, and the mix design has 5% binder and 95% aggregates, then 0.05 tons of binder and 0.95 tons of aggregate are required to produce 1 ton of HMA. If the unit process for binder determined that 100 megajoules (MJ) of total energy is consumed to produce 1 ton of binder, then 5 MJ of energy will be spent to produce 0.05 tons of binder for the 1 ton of HMA.

In a study that compares two different asphalt mixes, it would be incorrect to use an aggregated energy value for the materials in the mix based on a source in the literature for one mix and the calculation procedure outlined for the other, without explicitly stating why the two different calculation procedures were used, and how any problems with this approach could affect the comparison.

4.2.6 System Boundary Refining.

As noted previously, the initial results of the data collection phase may necessitate changes to the system boundaries. Two potential reasons for changing the system boundaries are difficulty measuring flows for which planning had determined that primary data would be used, or a lack of available data where secondary data was planned for use. System boundaries may also be changed if it is determined that certain unit processes are not significant based on the cut-off criteria for mass, environmental significance, or energy as determined from the goal and scope of the study (see section 3.4.2 for a discussion of cut-off criteria).

Sensitivity analysis can also help to refine the study’s scope. Sensitivity analysis may show that certain life-cycle stages or unit processes are not going to reach the level of critical significance estimated in the goal and scope of the study. This type of analysis may also show that certain inputs that were expected to fall below the critical cut-off levels will need to be included because they may have the potential to exceed the cut-off criteria. For example, the emissions from a commercial wax used in asphalt concrete production (to lower the mixing and compacting temperatures) at less than 1% by mass of mixture may fall below a 1% mass cut-off criterion.

However, an initial analysis may show that the wax contributes to the environmental impacts at a level high enough that it should not be cut off and placed outside the system boundaries. For infrastructure materials, it is not uncommon that chemicals with very small mass percentages still have environmental impacts or energy use large enough to require that they be included in the system boundaries based on the cut-off criteria discussed in section 3.4.2.

4.2.7 Allocation.

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 [6]. Allocation is used when a multi-product process cannot be broken into subprocesses that isolate the production of the product of interest. Allocation is also used when the boundaries between the current life cycle and the next life cycle are difficult to determine, such as when there is recycling of materials from one life cycle to the next. Allocation can be an issue in new materials production and can be particularly challenging where airfield infrastructure materials are produced from multi-product processes (asphalt, for example, which comes from oil refining). Allocation is also challenging where co-products, by-products, and recycled materials come from other industries, when pavement materials are reused in place, and when recycled pavement materials from other locations will displace use of virgin materials. The environmental flows and impacts related to the original manufacture of the materials to be recycled and their demolition, possible processing, and transport must be considered and allocated [4].

Some definitions and recommendations that are important for allocation of recycled materials are as follows:

- Recycled materials are those obtained from old pavement, fencing, wiring, or other infrastructure that are then included among the materials to be used in a new infrastructure feature. They can be processed and reused on an airfield, taken off an airfield and reprocessed for use on the same airfield or other airfields, or used for other applications elsewhere.

- It is generally recommended that the following cut-off criteria be used for existing materials that are recycled from within the current system, or brought into the system from other systems:

    - Exclude the processes of the original manufacturing and construction,

    - Include the transportation and processing needed if the material is reused on site,

    - Include the demolition but not the transportation and processing that are needed to prepare the material for use outside the system when the materials that are within the current infrastructure are to be recycled outside the current system,
    - Include the demolition, transportation, and processing needed to landfill material inside the current system if it is not to be reused anywhere, and

    - Include the transportation and processing needed to prepare recycled materials coming into the system from other systems.

- Co-products are derived as part of another process, often industrial but possibly agricultural, that brings economic value other than the cost of demolition, processing, and transportation 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 demolition, 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.

- By-product is not a term used in LCA as a material will either be a co-product or a waste depending on its economic value.

Double-counting is a problem directly applicable in airfield infrastructure LCA studies when the airfield infrastructure uses a waste product (i.e., it has no economic value) from an outside system and assumes that all of the environmental burden of producing that waste lies with its upstream producer, while at the same time the waste's producer reported a reduced environmental burden in producing the waste because of the downstream recycling in the airfield infrastructure. Some examples of where this can occur include the following:

- Construction demolition waste from buildings is used for granular base and subbase material.

- Fly ash from the burning of coal is used to reduce the use of cement.

- Iron blast furnace slag is used to reduce the use of cement and aggregate.

- Recycled tires are used in asphalt binders and other pavement applications.

- Recycled metals in wiring, steel reinforcement, fencing, and other metallic materials are used in airfield infrastructure.

Double-counting should be avoided.

4.2.8 Allocation Procedures for Co-Products and Wastes.

ISO guidelines recommend that allocation should be avoided whenever possible. The following are methods that can be used to avoid allocation:

- Break the unit process into subprocesses, and use the subprocesses that relate directly to the product of interest for the study.

- Expand the product system to include additional functions of the co-products, in such a way that the co-products are not treated as waste. Allocating impact to waste falsely reduces the impacts of the product under consideration.

If allocation cannot be avoided, the inputs and outputs should be partitioned, separating the products and functions based on the underlying physical relationships. If the physical relationship cannot be established or used, then the allocation procedure can follow other relationships. When avoiding allocation through subdivision or system expansion is not possible, ISO recommends allocation based on physical properties (e.g., mass, or energy content) or economic value. Currently, consensus does not exist on the preferred method of allocation for co-products. It is, however, generally accepted that the allocation method should incentivize practices that reduce environmental impact, prevent double-counting of recycling benefits, provide fairness between industries, and be transparent regarding how the allocation is conducted [19].

If there are multiple potential possibilities for allocation, which is generally the case for most airfield infrastructure materials that are co-products, then a sensitivity analysis must be performed to see their respective effects, and the results of the sensitivity analysis must be reported.

Allocation procedures should be applied in a uniform manner among products of similar nature.

4.3 APPLYING DECISION RULES FOR THE EXCLUSION AND INCLUSION (CUT-OFF) OF INPUTS AND OUTPUTS.

The initial exclusion rule was set in the goal and scope phase, and it is re-evaluated in the LCI phase after more was learned about the project. Inputs that were excluded from the system boundaries based on the initial criteria may be added later if it is determined that they have importance based on different criteria. For example, if mass was chosen as the cut-off criterion at first, but it is discovered that there are many products that have little mass and large environmental significance (e.g., additives, modifiers, etc.), it may become necessary to change the cut-off criteria to environmental significance (see section 3.4.2) and readjust the scope.

With a cut-off criterion finalized, the last step is to apply this criterion to the data collected and leave only what is still deemed significant for the remaining steps in the LCA.

There are two good practices for exclusion:

1. Include the information in an appendix.
2. Explicitly state what was excluded and the reasons for exclusion.

An example was presented by Butt et al. [61] in which authors developed a project-level LCA framework that determined the energy and GHG emissions of pavements at the procurement stage of the planning process. The study decided not to include the land area use stage since no impact and/or contribution on decision support was applicable at the procurement stage of the project. The decision to build a pavement has already been made at an earlier planning stage. It was suggested to include land area use stage in pavement LCA studies performed at the facility level or early planning stage of a project where it could influence decisions.

4.4 DATA COLLECTION STRATEGIES FOR EACH PAVEMENT LCA LIFE-CYCLE STAGE.

Potential data collection strategies for each life-cycle stage are listed in section 4.4.1. In each stage, data collection strategies are listed in numbered order, from most to least preferable.

4.4.1 Materials Stage.

The materials stage is the first stage that is considered in most life-cycle studies. If only the materials stage is considered in an LCA, the assessment may be called a cradle-to-gate study. In this stage, data collected mainly includes extraction of raw materials, processing, transportation, and storage of the materials to the point where they reach the gate of the storage or manufacturing facility to go to the airfield construction site. Each material has its own life cycle, and thus, the data to be collected must be considered for all materials involved in the system boundary unless they do not meet the cut-off rule. Possible ways of obtaining materials data are as follows:

1. Obtain emissions information directly from the producer/manufacturer from measurements or as published in a product-specific EPD.

2. Model the emissions based on known quantities of materials using a database or available emission factors.

3. Obtain emissions information directly from the producer/manufacturer from measurements or as published in an industry-average or regional-average EPD.

4. Calculate the quantities of materials based on plans and then model the emissions.

5. Estimate the design based on FAA design criteria for pavements, then back calculate the quantities to model the emissions.

6. Estimate the design based on the design of a similar or nearby airport, then back calculate.

7. Use the emissions from materials from a study in the literature of a different airport.

An EPD is an established way to declare the environmental impacts of a product. An EPD can be thought of as an LCA of a specific product with a scope limited to the cradle-to-gate stages of one product. EPDs from specific plants and for specific materials are preferable, as they allow the environmental comparison of alternative sources for a product. They are developed based on a set of rules, known as PCRs, which identify and describe the process of preparing the EPDs. The PCRs can be developed based on international standards such as ISO 14040 and 14044 [5 and 6] or handbooks such as the International Reference Life Cycle Data System [62].

There are mainly two types of EPDs: plant-specific or single-issue EPDs and average/industry-wide or sector-wide EPDs [63]. Plant-specific EPDs are LCAs of one or more products from a single company/plant. This EPD describes the life-cycle environmental impacts of product(s) and requires a valid PCR for the product. An industry-wide or region-wide EPD reports the average life-cycle impacts of product(s) from number of plants/companies in the same industry/sector and/or geographic region. Average EPDs are required to report whether a complete or partial PCR was followed, and the results reported are averages. Additionally, the names of the contributing companies/plants are required to be included in the document.

An example of a developed EPD system is that of the National Ready Mixed Concrete Association (NRMCA), under which concrete producers have published EPDs for different concrete mixes and has verified the EPDs under the NRMCA EPD program [64]. In 2017, the National Asphalt Pavement Association (NAPA) completed a PCR for asphalt mixtures [65]. EPDs exist for a number of other airfield infrastructure materials, and many other industries are developing PCRs so that they can begin submitting EPDs with their materials.

EPDs can motivate and guide product developers or material producers to improve the sustainability of their products using quantified, verified, and transparent impact indicators. The FAA could potentially use this system in the future as a requirement during procurement of materials [4 and 57].

The potential strategies for obtaining material data are as follows:

1. Obtain emissions impact information directly from the producer/manufacturer's EPD—if the producer has an EPD or can provide the information related to a given unit of material or infrastructure component, this should always be used. If an EPD from the producer of the material is unavailable but an EPD from a similar producer can be obtained, the latter may be used instead, provided that the justification is discussed. Plant/mix-specific EPDs are always preferable if available, otherwise industry-average EPDs can be used. The EPD needs to be checked to ensure that all the information needed was included in the system boundary of the EPD. For example, an EPD that can be obtained from a concrete plant should be used since it will already include the life-cycle impacts of the aggregate, cement, and additives for a specific mix.

2. Model the impacts using information from upstream flows into the material or infrastructure component—use upstream EPDs for flows into the material or infrastructure component, and calculate the impacts based on the proportions of the different materials in the mix design or complete infrastructure component. For example, EPDs from the next step upstream for a concrete mix would come from the aggregate producer, the cement producer, and any additive producers. Similarly, an EPD for a drainage or lighting system component can be used, if available; if an EPD for the complete system is unavailable, EPDs can be obtained for the materials used in those components and their impacts can be summarized based on the quantities of those materials in the component. Industry-average EPDs or EPDs from specific upstream producers can be used. If there is more than one upstream producer, then sensitivity analysis can include consideration of the alternative providers. This can be important if the specific materials or component suppliers are unknown at the time of the LCA.

3. Model the impacts for the material or infrastructure component based on known quantities of materials using a database of available emission factors—the total amount of each material may be known, but the manufacturer-specific impacts may be unavailable. The

environmental impact for a given unit of material should then be multiplied by the amount of material used. The environmental impacts using this strategy are typically taken from a commercial database such as the United States Life Cycle Inventory (USLCI) Database [66], Ecoinvent [67], etc., which use industry averages.

4. Calculate the quantities of materials based on the plans, and then model the emissions—there may be times when it becomes necessary to perform an LCA on a pavement, drainage system or other infrastructure component that is already in place. If the plans are available, it is possible to calculate the total volume of materials used. If assumptions are made, they need to be considered in the sensitivity analysis and documented.

5. Model the inputs using conceptual designs that are based on FAA design criteria for pavements or other infrastructure components, and estimate the impacts based on those typical designs—this approach is often needed when comparing alternatives at the conceptual stage of project development. If the design criteria for the pavement or infrastructure are available, it is possible to replicate the design process by taking into account the available information regarding the functional inputs—such as expected loads, climate, and dimensions of the feature—into the design process. Replicating the design process yields the estimated quantities of materials. If this method is used, it is necessary to show the calculations for the design in an appendix.

6. Estimate the impacts of the design based on the design of a similar feature at a nearby airport—smaller airports may not have a standard design process, so if plans are unavailable, the best course of action can be to look for similar airports where the designs of pavements and other airfield infrastructure are available. The relevance of the airports and infrastructure features chosen for comparison need to be listed and discussed.

7. Use the emissions from materials from a study of a different airport in the literature—this is the least preferable option, but it may be necessary where it is difficult to obtain any other information.

4.4.2 Construction and/or Manufacturing Stage.

The construction stage of the life cycle begins at the gate of the materials production plant for pavement and landscaping materials or at the manufacturing plant for infrastructure systems such as lighting, signboards, paints, drainage materials, and fences. In this stage, raw and/or processed materials or products are transported to the construction site at the airfield and paved, assembled, placed, and/or finished before being put into operation. This stage includes the operation of construction equipment and machinery, vehicle operation for transport, and any other on-site building/manufacturing/construction processes. The construction stage data can be collected in a number of ways:

1. Place sensors on the equipment used to measure emissions.

2. Obtain information about the total amount of fuel/electricity used for each piece of equipment and model the emissions based on how much each is used, ensuring that these

are tied to the types of operations and the size of the project; obtain estimates of all other products and processes required for the construction.

3. Obtain aggregated information about the total amount of fuel/electricity used in all the equipment and model the emissions; obtain aggregated estimates of all the other products and processes required for construction and model the emissions.

4. Obtain or estimate the horsepower and total number of equipment hours, and calculate energy use.

5. Estimate the throughput/capacity of the equipment known to be used, calculate the number of hours based on the material quantities or dimensions of the construction, and then calculate energy use.

6. Use past experience to determine expected types of on-site equipment to be used, then follow the same procedure as in step 5.

Some examples and explanation for each step are provided in the following list. The construction steps outlined also apply to calculating transportation emissions:

1. Place sensors on the equipment used to measure emissions. Connecting emissions-measuring devices to the exhaust pipe of a piece of construction equipment is the most reliable way to obtain accurate data is, if it is feasible. While capable of producing the best accuracy, this may not be feasible. Whether or not to use this difficult method of direct measurement will depend on the data needed and the amount of equipment used on site. Note that upstream emissions from fuel/electricity (energy resource production and transportation/transmission) must still be accounted for.

2. Obtain information about the total amount of fuel/electricity used for each piece of equipment and model the emissions. There are certain environmental impacts that vary from one piece of equipment to another (e.g., particulate matter (PM)). It is ideal to get the amount of fuel burned by each piece of equipment and then calculate the total environmental impacts using fuel production and combustion models. Fuel meters, for example, can be connected to a data logger in an excavator, dump truck, paver, or compactor to measure and record the exact amount of fuel injected for the amount of work done by that vehicle.

3. Obtain information about the total amount of fuel/electricity used by all the equipment and model the emissions. It is highly possible that individual emission rates for each piece of equipment cannot be obtained. If so, the best scenario is to obtain the total amount of fuel that was used at the construction site, construction project, or manufacturing plant and then estimate the environmental impacts from the combusted fuel/electricity used.

4. Obtain the horsepower of each piece of equipment and the total number of equipment hours, and calculate energy use. Equipment horsepower and use hours can be used to model fuel/energy use, but they add another layer of potential error. If the number of hours for

each piece of equipment is known, it is possible to assume a fuel rate and then calculate the total fuel used.

5. Estimate the throughput/capacity of the equipment and calculate the number of hours based on the material quantities, then calculate energy use. Where specific information about fuel use or machine-hours cannot be obtained, the hours can be estimated by using the throughput or capacity of the equipment. Throughput is defined as the amount of material or the area that can be processed over a given period of time. Therefore, with the amount of material or other dimensions known from the design or analysis of the materials stage, it is possible to estimate the number of equipment hours. For example, if the total amount of HMA is known and the type of paver is known, the amount of fuel burned by the paver to lay that amount of HMA can be calculated and later modeled to determine energy use.

6. Determine the types of on-site equipment, and then follow the same procedure as in step 5. When attempting to calculate construction effects it may not be possible to know exactly what equipment was or will be used. It is recommended to look at another study from the literature or to talk with a contractor or industry expert to determine what typical equipment is for that process. It is then possible to follow step 5.

4.4.3 The M&R Stage.

To analyze a full life cycle, the impacts of the materials and construction stages for each M&R activity that occur within the analysis period must be determined. The timing and types of maintenance or rehabilitation actions are generally assumed based on past experience or, where available, on pavement performance models for distress and/or roughness that will indicate when M&R would be triggered. The threshold conditions needed to trigger predicted treatments must be determined by the decision-makers in charge of the M&R and must be clearly documented. The preferred approach for estimating the type and timing of M&R activities, from most preferred to least is:

1. Create pavement initial condition value and deterioration curves based on time series construction and performance data from the airport asset management system, and use the curves to calculate the type and timing of M&R or replacement using established trigger values for performance variables. Ideally, deterioration curves for specific pavement designs or specific types of other civil infrastructure systems (fencing, drainage, etc.) based on the history of the airfield in question are available. It is a common practice for airports to conduct Pavement Condition Index (PCI) surveys every 3 or 5+ years, however, if airfield management does not have the appropriate data to create these curves, it is suggested that they start collecting and storing condition data in the asset management system to be used in the future.

2. Measure current pavement condition and assume a deterioration function to calculate type and timing of M&R or replacement. If a site-specific pavement deterioration equation is not available, an equation from the literature can be used. However, current pavement condition should be measured to make more accurate estimates for future condition.

3. Assume an initial condition and deterioration function to determine the type and timing of M&R or replacement. If the equipment to measure current pavement condition is not available, or the project has not been built yet, it is possible to assume a given level of pavement condition that is likely to occur after construction. If this method is chosen, it is necessary to perform sensitivity analysis on the level of condition.

4. Use M&R schedules taken from LCCA procedures.

5. Assume when M&R or replacement will occur based on an estimate from an industry expert. There may be cases where the available deterioration equations or M&R schedules will not be applicable. If this is the case, the next best option is to obtain an industry expert's opinion on how long the pavement will last. Obtaining more than one opinion and using a range of predictions as bounds for sensitivity analysis is suggested.

For each of the five different approaches, a sensitivity analysis should be performed to evaluate the effects of different assumptions for initial values of performance variable after construction and for deterioration curves.

Landscape maintenance includes sprinkler maintenance and replacement as well as the periodic replacement of materials, plants, etc. Information from original installation can be used.

Signboards, fences, and lighting can either be maintained on site by applying paint, realignment, or replacement. For repainting scenarios, data on paint production, on the paint quantities used, and on its transportation to the site need to be collected and recorded. Alternatively, the amount of paint used can be quantified by using the known the painted surface areas and locations, and then modeling the emissions.

This stage can also include the operations required to keep the pavement clean and ice-free. Data for any materials and vehicles or other equipment used for these operations should be collected following one of the approaches outlined above.

4.4.4 Use Stage.

The use stage includes the processes during which the user or consumer has control and/or access of the product. The impacts of operating the airfield infrastructure features, such as the energy used for lighting, signboards, drainage pumps, and water treatment plants, need to be determined. The influence of pavement characteristics and conditions on vehicle and aircraft operating energy, and potentially on vehicle and aircraft maintenance and replacement times should be considered. When comparing systems, differences in the impacts of passive features (such as storm water handling) should also be considered if they are part of the goal and scope of the LCA. The use stage data collection strategies for each component considered within the scope of this report are described in sections 4.4.4.1 through 4.4.4.5.

4.4.4.1 Airside Vehicles.

Several models exist to quantify the effect of pavement condition on vehicle operations; however, these models are typically based on continuous highway speeds and may not be accurate for the speeds at which the vehicles used on airfields travel. Acknowledging that the use of such models does not represent airfield land vehicle use entirely accurately however, to quantify the impacts of airfield land vehicle use, it is suggested to use the existing models until models are produced that can quantify the effect at lower speeds and under stop-and-start conditions that are typical of airfield land vehicle use. The practitioner should research to see if new studies were performed before using the models for highway speeds. The recommended approaches for considering airside vehicles are from most preferred to least:

1. For each vehicle, obtain the typical path it travels and the condition of the pavement along that path. Then apply models for the effects of pavement condition to calculate additional fuel consumption, tire wear, and additional maintenance. It is also necessary to calculate the expected deterioration of the pavement to quantify the effects of the pavement on the vehicle because the effects are greater with increasingly worse pavement condition. It is beneficial to know whether these vehicles mainly travel on runways or on aprons or other auxiliary roads since different pavement sections of an airfield will have different pavement conditions.

2. Obtain the total distance driven by each vehicle and the average pavement condition and extrapolate using the models and deterioration equations discussed in the first approach. The distances can be obtained by looking at the vehicle's odometer or log books and calculating the changes over a period of time (e.g., picking several vehicles and examining the difference over the course of one week or some other time period). Pavement condition should be measured.

3. Estimate the total number of miles driven by the vehicles and assume pavement condition based on initial construction condition and a deterioration model. It may be possible to estimate the number of miles that a vehicle travels based on the distances between various locations in the airfield.

4.4.4.2 Aircraft.

As of this writing, models to quantify the effect of pavement condition on the operations, maintenance schedules, or replacement life of aircraft were unavailable. This is an important gap for airfield LCA and requires cooperation from aircraft manufacturers to provide information regarding the effects of pavement on aircraft fuel burn, maintenance frequency, and life. Significant progress was historically made in this area by the World Bank and the FHWA.

4.4.4.3 Drainage.

The function of a drainage system is to collect, store, and convey surface runoff water away from the pavement structure to protect the structure. It may also include treatment or filtering of storm water. In the drainage use stage, runoff, infiltration (water entering the soil through drains), and water treatment/recycling (removing pollutants from runoff water) are considered. Runoff can be analyzed using mathematical models and water quality sampling methods. Pavement runoff pollutants such as heavy metals, inorganic salts, aromatic hydrocarbons, etc., can be measured using different water quality analysis equipment. Data driven models (DDMs) can be used as an alternative. DDMs are being used in water and environmental research, and were also used for pavement runoff pollutants [68].

4.4.4.4 Lighting.

The lighting use stage consists mainly of electricity consumption after the lighting is installed. A separate electricity measuring meter can be installed to isolate the energy used by the pavement lighting system. If this type of measurement is not possible, electricity consumption can be calculated based on the information about the bulbs/light-emitting diodes (LEDs)/luminous tubes used for the lighting. For example, a 100-watt bulb consumes 100 J of energy per second. Total energy can then be calculated based on the functional unit of the study.

4.4.4.5 Landscaping.

Landscaping in the use stage consists mainly of irrigation, fertilizing, and operations such as mowing. The amount of water used for irrigation can be calculated by metering, although in certain cases this may be expensive or not feasible. Water quantity can also be calculated by determining the capacity/efficiency of a sprinkler and then recording the time it is operational. The quality of the water leaving the system boundaries can be determined by measurement or from modeling for different types of landscaping, deicing, etc. The mowers used for landscaping can either be instrumented with fuel and emissions meters/equipment or modeled for fuel consumption and emissions using their horsepower values and hours of operation.

4.4.5 The EOL Stage.

The EOL stage consists of two stages: recycling (materials that can be reused) and waste (useless/functionless materials). A life cycle of a product/system ends once the material is recycled (i.e., used in another project/geographic location) or when it loses its function and is either incinerated or landfilled as waste.

4.4.5.1 Recycling.

Recycling is a process in which a material can be reused and/or reprocessed into some other useful/consumable product. Pavement materials are mainly recycled and reused either in the same pavement/project or in another project/geographic location. Once the pavement materials cannot be recycled further, they are usually used as substructure materials and remain part of a pavement structure, and hence, they cannot be called waste. Asphalt mixtures can be recycled into reclaimed asphalt pavement (RAP) material and reused. Similarly, concrete can be recycled as recycled concrete aggregate (RCA) and reused as base material. Metallic products such as fences, signboards, and lighting poles are usually recycled when they reach EOL. Recycling and reuse within the same project/location are what is called closed-loop recycling; the process in which a material is recycled into another product is referred to as open-loop recycling. The biggest challenge in recycling is allocation. The cut-off rules for allocation for recycling discussed in section 4.2.7 are applicable to both processes.

The only energy and emissions data involved in recycling occur in the process of reprocessing/remixing the materials on site and/or transportation of the materials to the mixing/production/manufacturing plant, processing the materials, and their transportation back to the construction site. Material data collection strategies applicable to these situations were discussed in section 4.4.1 pertaining to the materials and construction stages.

4.4.5.2 Waste.

The life cycle of a system is complete when it ends up as waste and is either incinerated or buried as landfill. Pavements materials usually remain part of the structure (see section 4.4.5.1); that is, there is no EOL for these materials. waste metals and other materials from lighting, signboards, drainage, and fences may need to be transported to a landfill or incinerator. The impacts from transportation of waste, landfilling, leaching from waste, and incineration do need to be reported and included in the life-cycle study, but the percentage of material(s) collected as waste can be recorded and then calculated in the life-cycle study. Fuel combusted and emissions from the transportation of waste to the landfill site/incinerator can also be recorded following the procedure described in section 4.4.2. The Waste Reduction Model [69] developed by the U.S. Environmental Protection Agency (EPA) can be used as an example for modeling/calculation of the emissions from landfill waste.

4.5 COMMONLY USED DATA SOURCES.

Qualitative and quantitative secondary data can be collected from different sources such as databases, LCA literature, public documents, surveys, etc., when primary data is unavailable. It is important to select data based on the data quality requirements determined in the goal and scope phase. Several data sources are discussed in this document, and some examples of data sources are shown in table 8. The number of studies specific to airfield pavement (see section 2) is relatively small compared to those available on highway pavements. However, LCA is a rapidly growing field and readers are encouraged to search for new and more relevant information than previously published literature. Table 8 is a version of the data sources table that appears in the FHWA Pavement Life-Cycle Assessment Framework that was augmented to include the available airfield LCA sources [19 and citing 3, 43, 47, 61, 66 and 70 through 135].

Table 8. Data Collection Stages, Processes, and Sources

Data Collection Stage	Unit Process	Data Sources
Materials	Asphalt mixture production	Ecoinvent 3.1[70], Hot mix asphalt plants emission assessment report [71], EIO-LCA [43], Butt et al. [61, 72, and 73], Stripple [74]
	Ready mix concrete production	Ecoinvent 3.1 [70], Portland Cement Association (PCA) [75], Medgar [76], Nisbet et al [77]; Nisbet et al [78]
	Asphalt binder production	Ecoinvent 3.1 [70], Eurobitume [79]
	PCC manufacturing	Ecoinvent 3.1 [70], Marceau et al. [80], EIO-LCA [43], Huntzinger and Eatmon [81], Valderrama et al. [82], Josa et al. [83]
	Paint products	Hanssen [84]
	Steel manufacturing	World Steel [85], Ecoinvent 3.1 [70]
	Aluminum	World Aluminum, [86 and 87]
	Lighting	Hartley et al. [88], Welz et al. [89], Stripple [90]
	Fencing/road signs/poles	Stripple [90]
	Drainage	EcoInvent 3.1 [70], USLCI [66], and European Life Cycle [91] databases
	Aggregate production	Crushed Stone Emission Factors chapter [71], Sand and Gravel Processing Emission Factors chapter [71], PCA [75], Korre and Durucan [92], Jullien et al. [93], Meil [94], Häkkinen and Mäkelä [95], Butt and Birgisson [73]
Construction and M&R	Equipment emissions and fuel use	EPA [96], Wang et al. [47], Skolnik, Brooks, and Oman [97]
	Runways, taxiways, parking, apron pavements	Sources mentioned in Chester [3], FAA [98], PaLATE [44], EPA [99]
	Paint application	Pappasava [100]

Table 8. Data Collection Stages, Processes, and Sources (Continued)

Data Collection Stage	Unit Process	Data Sources
Airside Vehicles Use Stage	Albedo	Akbari et al. [101], Akbari and Matthews [102], Li et al. [103 and 104], Pomerantz et al.[105]
	Rolling resistance	Karlsson et al. [106], Karlsson et al. [107], Hammarström et al. [108 and 109], Bergiers et al. [110], Sandberg et al. [111]
	Stiffness	Taylor and Patten [112], Ardekani and Sumitsawan [113], Bienvenu and Jiao [114], Hultqvist [115], Thom et al. [116], Pouget et al. [117], Akbarian et al. [118], and Chupin et al. [119]
Aircraft Use Stage	Landing and Takeoff (does not include pavement effect)	Chester [3], FAA [120]
Drainage Use Stage	Water pollution from leachate and runoff	EPA IWEM [121]
Lighting Use Stage	Lighting	Energy Efficiency and Renewable Energy (EERE) [122]
EOL Stage	Waste	Doka [123 and 124], database on waste management technologies [125]
Transportation	Hauling truck/rail/barge	EPA MOtor Vehicle Emission Simulator (MOVES) [126], Ecoinvent 2.2 [127], IPCC Emission Factors [128], Agrawal et al. [129], Wang et al. (covers California Air Resources Board (CARB) EMFAC model and CARB OFFROAD model) [47], SimaPro [130]
Fuel and Electricity	Fuel	GREET® [131 and 132], Ecoinvent 2.2 [127], Skone and Gerdes [133], NONROAD [96], SimaPro [130], International Energy Agency (IEA) [134]
	Electricity	Ecoinvent 2.2 [127], SimaPro [130], IEA [134], EPA eGRID [135]

4.6 DATA COMPLETION.

A data completeness check should be performed to determine the degree to which data are complete and if the cut-off criteria were met. If the cut-off criteria were not met, additional and better data would need to be collected to fulfill the goal and scope requirements (i.e., revisit the LCI for improvements). Alternatively, if the data is incomplete, the system boundaries may need to be refined by revising the goal and scope of the study [6 and 62].

4.7 DATA QUALITY ASSESSMENT.

The quality of all the data used in the study should be assessed. ISO 14044 [6] defines data quality as the "characteristics of data that relate to their ability to satisfy stated requirements" of the goal and scope of the study. A thorough data quality assessment assists with locating potential sources of uncertainty and is useful in identifying gaps in the data that can be updated as better sources become available. These following data quality criteria [6] are considered to be a minimal set that should be applied.

- Time-related coverage—the assessment should include the age of the data, i.e., when it was collected or how old it is. This provides an indication of the data's relevance to current processes, since the efficiencies of most technologies improve with time and the materials in products often change.

- Geographic coverage—the geographic location where the data was gathered also needs to be reported and the data checked to determine whether they satisfy the quality requirements. Processes and materials vary from region to region. Justification is to be provided when using data that are not from the same region.

- Technology coverage—technology changes, typically improving with time. The assessment of the current relevancy of the specific technology and/or technology mix assumed in the study is required.

- Precision—the level of precision of the data needs to be assessed. This will help provide an indication of the uncertainty surrounding the values used in deterministic analyses.

- Representativeness—an assessment of the applicability of the data to the system should be provided.

- Reproducibility—the methodology and data should be reported and presented so that others can recalculate/replicate/duplicate/reproduce the results.

- Completeness—a check of whether all the required data meet the requirements of the goal and scope should be provided. If the completeness check identifies deficiencies, then additional data must be gathered or modeled.

- Consistency—a check of whether the methodology used in collecting the data was applied consistently should be made, and inconsistencies should be documented and justified.

- Data sources—the credibility of data also depends on its source. The sources need to be critically analyzed and/or assessed before any of the data is shown to be reliable.
- Uncertainty of the information—data, models, and assumptions need to be assessed for uncertainty.

Other information that can be provided includes the independence of the data supplier (verifying whether the acquired data has been assessed by reviewer(s)), the method of acquisition (whether the data is measured, assumed or acquired), and the impact on results (how important is the information and/or data), as well what could be included to further improve the quality of data and thereby lead to more reliable results.

To make the data quality assessment easy to comprehend, and to save time and space in cases where many data sources are used in the LCA, creating what is known as a pedigree matrix is recommended. A pedigree matrix assigns quality scores ranging from 1 to 5 for each of the data quality criteria, with specific descriptions for each numeric value for each criterion. Table 9 shows an example of a data quality assessment pedigree matrix [28] that lists the required criteria. Using the data pedigree matrix in table 9 as a starting point is recommended, adjusting or adding criteria as necessary. An example data quality assessment from UCPRC is shown in table 10 [136].

Table 9. Data Quality Assessment Pedigree Matrix

Criteria	Indicator Score				
	1	2	3	4	5
Impact on final result	Parameter is the top contributor to final result	Parameter is within the top 5 contributors to final result	Parameter is within the top 10 contributors to final result	Parameter is not likely to affect final results significantly	Parameter contribution is unknown
Acquisition method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Nonqualified estimate
Independence of data supplier	Verified data information from public or another independent source	Verified information from enterprise with interest in the study	Independent source, but based on nonverified information from industry	Nonverified information from industry	Nonverified information from the enterprise interested in the study
Representation	Representative data from sufficient sample of sites over and adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but from shorter periods	Data from adequate number of sites, but shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area of study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology

Table 9. Data Quality Assessment Pedigree Matrix (Continued)

Criteria	Indicator Score				
	1	2	3	4	5
Range of variation	Estimate is a fixed and deterministic number	Estimate is likely to vary within a 5% range	Estimate is likely to vary within a 10% range	Estimate is likely to vary more than 10%	Estimate is likely to vary under unknown ranges

.

Table 10. A UCPRC LCI Data Quality Assessment

Item	Time-Related Coverage	Geographical Coverage	Technology Coverage	Source of Data	Reproducibility	Notes
Aggregate—crushed	Good	Good	Good	GaBi/Lit.*	Y	Used GaBi for modeling based on literature and calibrated based on California grid mix and plant fuel.
Aggregate—natural	Good	Good	Good	GaBi/Lit.	Y	Used GaBi for modeling based on literature and calibrated based on California grid mix and plant fuel.
Bitumen	Excellent	Good	Good	GaBi/Lit.	Y	Used GaBi for modeling based on literature and calibrated based on California grid mix and plant fuel.
Bitumen emulsion	Excellent	Good	Good	GaBi/Lit.	Y	Used GaBi for modeling based on literature and calibrated based on California grid mix and plant fuel.

Notes: GaBi is a life-cycle assessment tool licensed by Thinkstep software company.

5. THE LCIA.

The purpose of an LCIA is to translate the results from an LCI into impact indicators for the natural environmental, human health, and resource depletion. Impact indicators are calculated from models that relate the LCI flows to impacts by using characterization factors for each impact category. There are a number of different impact indicators, and there are different methods to calculate impacts within different LCIA approaches.

Indicators can include aggregated flows, midpoint indicators, and endpoint indicators. Energy consumption is an example of an aggregated flow, as is the emission of particulate matter smaller than 10 micrometers (PM_{10}). Ozone depletion is an example of a midpoint indicator, and flows of various emissions into the air can be used with their associated characterization factors to determine this impact. Human health is an example of an endpoint indicator where either the total damage or the final environmental impact on human health is calculated from a number of midpoint indicators. Both the inputs and outputs from a system can contribute to impact indicators. Figure 15 shows the LCIA process flow diagram in accordance with ISO 14044 [6].

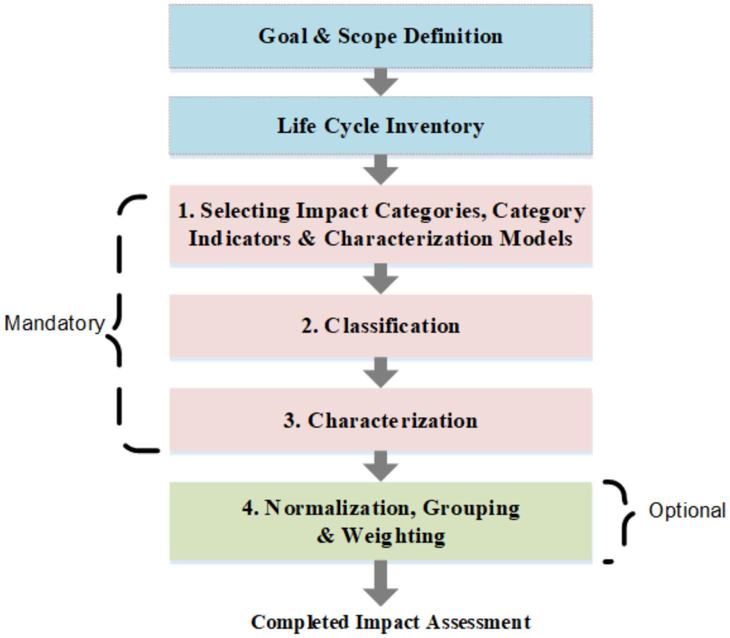


Figure 15. The ISO Recommended Process for LCIA

There are three possible omissions or sources of uncertainty that need to be addressed as part of the LCIA phase [6]:

1. Whether the quality of the data from the LCI phase is sufficient to conduct the LCIA phase based upon the goal and scope of the study.

2. Whether the decisions surrounding the system boundary and cut-off criteria have been reviewed in a manner that makes it possible to calculate the indicator results for the LCIA.

3. Whether changing the functional unit, allocation, aggregation, or averaging has decreased the relevance of the LCIA results.

According to ISO 14044 [6], there are three mandatory elements and three optional elements of an LCIA. The inclusion of any of the optional elements in an LCA study has to be documented in its goal and scope.

The following elements are categorized as mandatory:

- Selection of impact categories, category indicators, and characterization models.
- Classification, which is the assignment of LCI results to the selected impact categories.
- Characterization, which is the calculation of category indicator results.

The three optional elements include:

- Normalization
- Grouping
- Weighting

5.1 MANDATORY ELEMENTS OF LCIA.

5.1.1 Selection of Impact Categories, Category Indicators, and Characterization Models.

Impact categories are specific environmental problems/concerns to which the LCI results are assigned. The impact categories can be related to inputs such as resource and energy consumption, or to outputs such as the effects of pollutant(s). Category indicators are measures that define or indicate the magnitude of the environmental impact. They can be selected at any level midpoint between the LCI results and their aggregated flows and the endpoint indicators. Characterization models describe the relationship between the LCI results and the category indicators. Characterization factors are obtained from the characterization models, and these factors translate the emissions within an impact category to its category midpoint or endpoint.

As an example, a fence manufacturer could conduct an LCA study to determine the effect on GWP and climate change attributable to the total pole/fence production in 2010. GWP describes the total effect of all/considered GHG emissions, such as CO_2, nitrous oxide (N_2O), and methane (CH_4), in the analysis period calculated in CO_2-e using models that relate the amount of GWP each gas creates. The manufacturer would measure and record the mass of GHG emissions for each gas type from each production process for the functional unit that was defined in the goal and scope of the LCA study. The GHG emissions, expressed as kg per functional unit, are the LCI flows. Climate change is the endpoint impact category, and GWP is the category indicator (midpoint indicator). The characterization model relates how each gas contributes to global warming.

The data and their sources need to be referenced for every impact category, category indicator, and characterization model that is used in the LCIA. If a new category, indicator, or characterization model is being created, then a full explanation and appropriate reference for how and why it was created must be made explicit in the LCA. The goal and scope are used to guide the choices of impact categories, category indicators, and characterization models needed to answer the questions posed in the goal.

Hauschild et al. [137] described the following scientific criteria for choosing a characterization model, which should be discussed in the LCA:

- Completeness of scope: How well do the indicator and the characterization model cover the environmental mechanisms associated with the impact category under assessment?

- Environmental relevance: To what extent are the critical parts of the impact pathway included and modeled in accordance with the current state of knowledge? This is thought of as the “burden to impact pathway”, meaning that it describes how an emission or resource use (the burden) contributes to an impact, quantified by a category midpoint indicator through a model of a scientifically validated mechanism.

- Scientific robustness and certainty: How well has the model been peer reviewed, does it represent state of the knowledge, can it be validated against monitoring data, and are uncertainties reported?

- Documentation, transparency, and reproducibility: How accessible are the model, the model documentation, the characterization factors, and the applied input data?

- Applicability: Are characterization factors provided for the important elementary flows for this impact category in a form that is straightforward to apply?

- Stakeholder Acceptability: Are the stakeholders who will be evaluating or receiving the results of the LCA familiar with or accepting of the model chosen?

Developed by the U.S. EPA, the TRACI is the recommended system for environmental impact indicator calculation and calculating midpoint indicators. Table 11 shows the current version [54] of the TRACI indicators and impact categories. Additional details on TRACI indicators are also provided in section 5.4.

Table 11. The TRACI Indicators and Impact Categories

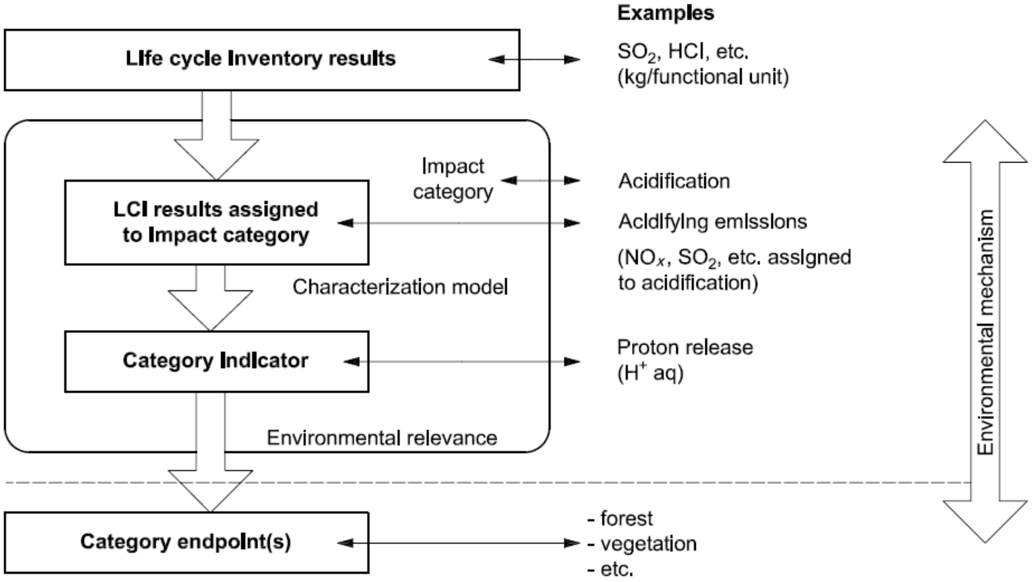
Impact Category	Midpoint Level Selected	Level of Site Specificity Selected	Possible Endpoints
Ozone depletion	Potential to destroy ozone based on chemical’s reactivity and lifetime	Global	Skin cancer, cataracts, material damage, immune- system suppression, crop damage, other plant and animal effects
Global warming	Potential global warming based on chemical’s radiative forcing and lifetime	Global	Malaria, coastal area damage, agricultural effects, forest damage, plant and animal effects
Acidification	Potential to cause wet or dry acid deposition	U.S., east or west of the Mississippi River, U.S. census regions, states	Plant, animal, and ecosystem effects, damage to buildings
Eutrophication	Potential to cause eutrophication	U.S., east or west of the Mississippi River, U.S. census regions, states	Plant, animal, and ecosystem effects, odors and recreational effects, human health impacts
Photochemical smog	Potential to cause photochemical smog	U.S., east or west of the Mississippi River, U.S. census regions, state	Human mortality, asthma effects, plant effects
Ecotoxicity	Potential of a chemical released into an evaluative environment to cause ecological harm	U.S.	Plant, animal, and ecosystem effects
Human health: criteria air pollutants	Exposure to elevated PM less than 2.5 micrometer	U.S., east or west of the Mississippi River, U.S. census regions, states	Disability-adjusted life years (DALYs), toxicological human health effects

Table 11. The TRACI Indicators and Impact Categories (Continued)

Impact Category	Midpoint Level Selected	Level of Site Specificity Selected	Possible Endpoints
Human health: cancer	Potential of a chemical released into an evaluative environment to cause human cancer effects	U.S.	Variety of specific human cancer effects
Human health: non-cancer	Potential of a chemical released into an evaluative environment to cause human non-cancer effects	U.S.	Variety of specific human toxicological non-cancer effects
Fossil fuel	Potential to lead to the reduction of the availability of low cost/energy fossil fuel supplies	Global	Fossil fuel shortages leading to use of other energy sources, which may lead to other environmental or economic effects
Land use	Proxy indicator expressing potential damage to threatened and endangered species	U.S., east or west of the Mississippi River, U.S. census regions, state, county	Effects on threatened and endangered species (as defined by proxy indicator)
Water use	Not characterized at this time		Water shortages leading to agricultural, human, plant, and animal effects

As an example, chlorofluorocarbons (CFCs) emitted from electronic appliances and aerosol cans cause ozone depletion (reduction of the oxygen layer about 90,000 feet above the earth's surface that protects the environment from ultraviolet (UV) radiation). Chlorine gas, which is formed in the ozone layer due to the exposure of CFCs to UV light, depletes the ozone in the ozone layer resulting in less UV light being filtered. The midpoint indicator for this example calculated using a model of the effects of chlorine gas on ozone depletion in the atmosphere is the potential for ozone layer depletion due to the emission of CFC and other gases with similar mechanisms. The endpoint indicator is the final/end effect, such as skin cancer or material damage, that is caused by the increase in UV light exposure due to the depletion of the ozone layer (see table 11). The burden to impact pathway is from burden of the gas emission flows to the impact of ozone depletion, quantified by the ozone depletion midpoint (category) indicator, with the pathway then continuing to a human health endpoint indicator.

Another example of an impact category indicator, acidification, is shown in figure 16 [6]. In this LCIA example, emissions were quantified in the LCI analysis and certain emissions that contribute to acidification were assigned (see section 5.1.2) to the acidification impact category. It should be noted that the LCI results in figure 16 are the flows (burden), and the category indicator is the midpoint indicator. The potential to cause wet or dry acid deposition is considered to be a midpoint indicator, whereas the actual effects of acidification on the forest vegetation are considered to be the endpoint indicator. There may be other midpoints, with any indicator occurring after the quantification of flows in the inventory analysis and before the endpoint indicator, considered a midpoint indicator.



Note: the LCI results are the flows (burden), and the Category Indicator is the midpoint indicator.

Figure 16. Acidification Impact Category Within LCIA

5.1.2 Classification.

In the classification part of the LCIA phase, the inventory parameters are sorted and assigned to specific impact categories.

Assignment of LCI results to different impact categories should be based on the following [6]:

- LCI results that are exclusive to one impact category
- LCI results that relate to more than one impact category, including
    - Those that flow through between parallel mechanisms (e.g., sulfur dioxide (SO_2) is classified to contribute to these impact categories of human health: non-cancer and acidification), and
    - Those that flow through serial mechanisms (e.g., NO_x can be classified to contribute to both ground-level ozone formation and acidification).

5.1.3 Characterization.

Characterization is the impact measurement part of the LCIA phase where the LCI flows are characterized using an LCIA methodology to achieve a common equivalence unit that provides an overall impact category total. ISO 14044 [6] states that "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 uses characterization factors. The outcome of the calculation is a numerical indicator result." The results can be at a midpoint (cause-effect or reference flow) or an endpoint (damage effect) level based on what is described in the goal and scope of the study. Characterization factors are different for midpoint and endpoint levels.

LCIA involves evaluation of the environmental effects, human impacts, and resource depletion including the calculation of LCA results through classification and characterization. An example of a complete LCIA process is shown in figure 17.

In this example, the material production and construction processes for an asphalt runway overlay are considered, and these processes emit certain gases. The gas emissions are grouped (classified) based on their contribution to the selected impact categories. Using the global warming impact category as an example, the midpoint indicator is GWP, and the endpoint indicator is a measure of the climate change that results from the global warming. Similarly, the flows of acid-forming gases released into the air contribute to the acidification potential (midpoint indicator), which causes acid rain and leads to crop loss (endpoint indicator).

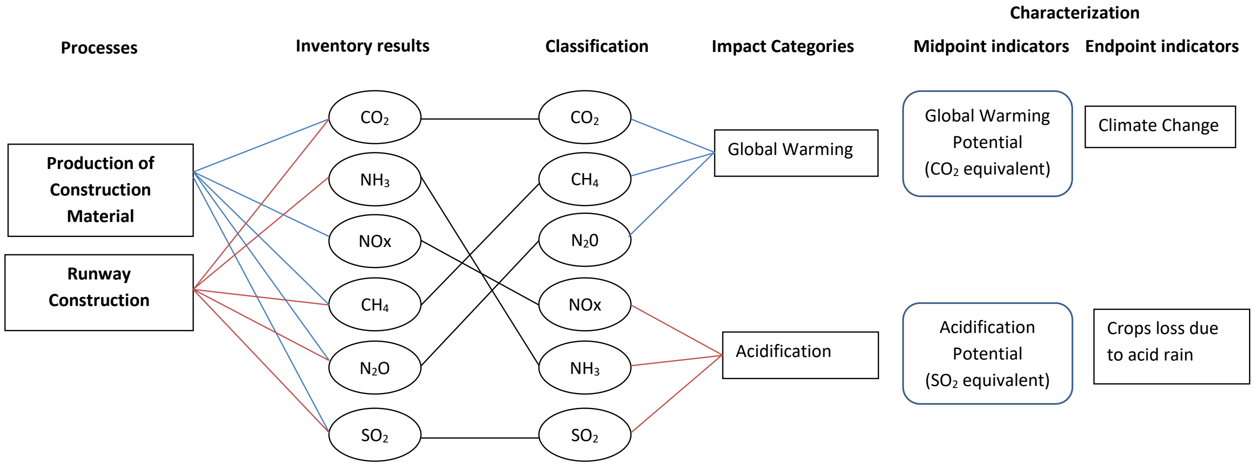


Figure 17. Classification and Characterization of Different LCIA Phases

Although it may appear as double-counting, the calculation of more than one impact indicator from the same flow is allowable if the multiple impact indicators are called for in the goal and scope of the study. For example, emissions that damage human health by damaging the respiratory system can also contribute to acidification.

5.2 OPTIONAL LCIA ELEMENTS.

5.2.1 Normalization.

According to ISO 14044 [6], normalization is the process of "calculating the magnitude of category indicator results relative to reference information." The aim of normalization is to improve the understanding of the relative magnitude for each indicator result of the product system under study. It can help check for inconsistencies, provide and communicate information on the relative significance of the results, and make the data ready for additional procedures, such as grouping, weighting, or interpretation. Normalization transforms an indicator result by dividing it by a selected reference value. None of the TRACI impact categories shown in table 11 were subjected to normalization [138].

As an example of normalization, GHG emissions in the U.S. were estimated to be around 6,669 million metric tons (tonnes) of CO_2-e in 2010. With the U.S. having a population of 309 million that year, per capita GHG emissions were 21.5 tonnes of CO_2-e. Normalizing of GHG emissions to per capita values can change the conclusions from the LCIA phase and can change the interpretation of the results and recommendations, depending on the questions to be answered as defined in the goal and scope.

For example, one LCA study that did not use normalized results found that the depletion of the natural resources impact category had a much greater value for one alternative than another also under consideration. However, a deeper analysis of the LCA showed that the study site had a thousand-year supply of those same resources, which indicated that the depletion was less important than other impact categories.

5.2.2 Grouping.

ISO 14044 [6] defines grouping as “the assignment of impact categories into one or more sets as predefined in the goal and scope definition.” It may also involve sorting and/or ranking. Grouping has two different possible procedures: sorting the impact categories on a nominal basis (e.g., by characteristics such as inputs and outputs or global regional and local spatial scales), or ranking the impact categories in a given hierarchy (e.g., high, medium, and low priority). 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 indicator results or normalized indicator results.

The main reason grouping is used is to help organize the impact information for the many indicators into a system for arriving at conclusions. This can be particularly important when a full set of indicators is calculated in the impact assessment, and they produce results that move in opposing directions for different indicators for the alternatives being compared. Grouping involves sorting to reduce the number of impact categories to one or two, such as grouping into air impacts, water impacts, resource impacts, and soil impacts, and/or ranking based on the priorities of the decision-making organization identified in the goal and scope. For example, the organization may define that global warming, human health, and water use have high priority, and acidification and land use have low priority in terms of arriving at their decision.

5.2.3 Weighting.

Weighting is defined by ISO 14044 [6] as “the process of converting indicator results of different impact categories by using numerical factors based on value-choices.” It may include aggregation of the weighted indicator results to arrive at a single parameter for comparison of alternatives. The most common weighting methods are panel weighting and distance-to-target. In the panel weighting method, a panel of LCA experts and users assesses the relative importance of each impact category and determines the weights. Such an approach was used in the Eco-indicator 99 [139] and the ReCiPe [140] methods. In the distance-to-target method, the severity of an impact is based on the difference between measured existing emission levels in a geographic location and the level considered to be critical (target level). The ecological scarcity method [141] uses this method. Weighting is determined by value-choices rather than on a scientific basis and must be tied to the goal and scope of the LCA. It is important to note that ISO does not allow weighting to be used in comparative assertions disclosed to the public.

Different individuals, organizations, and societies may have different preferences, and 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 analysis to assess the consequences on the LCIA results of different value-choices and weighting methods. It is recommended that data and indicator results or normalized indicator results reached prior to weighting be made available together with the weighting results. This ensures that trade-offs and other information remain available to decision-makers and to others, and practitioners can understand the ramifications of the weighting on the results.

5.3 ADDITIONAL LCIA DATA QUALITY ANALYSIS.

Additional techniques and information may be needed to form a better understanding of the significance, uncertainty, and sensitivity of the LCIA results. The results of further analysis may help distinguish if significant differences are present, identify negligible LCI results, or guide the iterative LCIA process. Whether another technique is needed and which one(s) to use will depend on the accuracy and detail required to fulfill the goal and scope of the LCA. Since LCA is an iterative process, data quality analysis may require revision of the entire LCI phase. More specific data quality analysis techniques proposed by ISO 14044 [6] include the following:

- Gravity analysis—this process involves uses a statistical procedure to ensure better decision support by identifying and prioritizing data that has greater contribution to the indicator results.

- Uncertainty analysis—this process is useful for determining the propagation of uncertainties in data and calculations that affect the reliability of the LCIA results.

- Sensitivity analysis—this is used to determine the effects of changes in data and methodology on the LCIA results.

5.4 COMMONLY USED IMPACT INDICATOR SYSTEMS.

TRACI, which was described in section 5.1.1, is the only impact assessment methodology that is regionalized to the U.S. and is recommended for use by the FHWA pavement LCA guidelines. The following impact categories are included in TRACI (table 11) [54]:

- Ozone depletion—a reduction in the thickness of the ozone layer in Earth’s stratosphere that absorbs harmful (type B) UV rays and prevents UV light from reaching the planet’s surface. The consequences of ozone layer depletion include skin cancer, crop damage, visual impairment, sunburn, etc.

- Climate change—changes in weather conditions and temperatures observed over a long period of time. In TRACI climate change is used in the context of global warming, which is the increase in the global temperatures. This effect causes sea-level rise (due to melting glaciers), higher temperatures globally, damage to forests/agriculture, etc.

- Acidification—an increase in the acidity (H^+ ions) of water and soils. This affects ecosystems in number of ways, including crop destruction, effects on water quality, the death of plants and animals, etc.

- Eutrophication—an increase of the nutrients in fresh water (lakes, rivers, etc.) which causes an increase in the growth of plant life (mainly algae); it leads to reductions of water oxygen content and thereby endangers marine animal life. It also affects water quality in a way that may harm humans and livestock.

- Tropospheric ozone (smog) formation—ozone (O_3) is naturally formed in trace amounts in the atmosphere. Due to certain emissions (NO_x, volatile organic compounds) that react in sunlight and increase the production of ozone gas in the troposphere, this may lead to detrimental impacts on human health (respiratory diseases, birth defects, deaths, cancers, etc.) and ecosystems.

- Ecotoxicity—any chemical or stressor that may affect an ecosystem (which includes humans, animals, and/or plants).

- Human health criteria pollutants—PM (particles less than 2.5 micrometer in size) or particle pollution that leads to human health issues such as respiratory problems, increases in mortality rates, etc.

- Human health cancer effects and non-cancer effects—chemicals released into the environment that have the potential to cause toxicological impacts that lead to cancer or non-cancer effects in humans.

- Resource depletion—excessive use of natural reserves such as fossil fuels, water, and land that may lead to use of other natural resources, and hence lead to detrimental environmental effects.

Impact categories can also be selected from the European Standard for Sustainability of Construction Works [12]. The impact categories that are considered in the standard include global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, depletion of abiotic resources (elements), and depletion of abiotic resources (fossil). Table 12 shows the environmental parameters compiled from tables in EN 15804 [12].

Water use has not been characterized in TRACI. Therefore, where the goal and scope call for a water use indicator, it is recommended to use the EN 15804 [12] water use indicator along with the TRACI indicators. Furthermore, the approach mentioned in EN 15804 [12] for energy flows (shown in table 12) in the FHWA pavement LCA guidelines [19] is to be used instead of the primary energy consumption indicator often used in TRACI. In the EN 15804 [12] approach, different types of renewable and nonrenewable energy are reported separately rather than in one accumulated value, as shown in table 12.

Table 12. Parameters Describing Environmental Impacts

Impact Category	Parameter	Unit (expressed per functional unit or per declared unit)
Global Warming	Global warming potential (GWP)	kg CO_2-e
Ozone Depletion	Ozone depletion potential (ODP)of the stratospheric ozone layer	kg CFC 11-e
Acidification for soil and water	Acidification potential (AP) of soil and water	kg SO_2-e
Eutrophication	EP	kg $(PO_4)_3$-e
Photochemical ozone creation	Formation potential of tropospheric ozone, photochemical ozone creation potential (POCP)	kg Ethene-e
Depletion of abiotic resources-elements	Abiotic depletion potential (ADP-elements) for nonfossil resources	kg Sb-e
Depletion of abiotic resources-fossil fuels	Abiotic depletion potential (ADP-fossil fuels) for fossil resources	MJ, net calorific value
Resource use	Use of renewable primary energy excluding renewable primary energy 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 energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value

Table 12. Parameters Describing Environmental Impacts (Continued)

Impact Category	Parameter	Unit (expressed per functional unit or per declared unit)
Resources use (continued)	Use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials	MJ, net calorific value
	Use of nonrenewable primary energy resources used as raw materials	MJ, net calorific value
	Total use of nonrenewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value
	Use of secondary material	kg
	Use of renewable secondary fuels	MJ, net calorific value
	Use of nonrenewable secondary fuels	MJ, net calorific value
Water use	Net use of fresh water	m^3
Waste	Hazardous waste disposed	kg
	Nonhazardous waste disposed	kg
	Radioactive waste disposed	kg

Notes:
CO_2-e = Carbon dioxide equivalent
SO_2-e = Sulfur dioxide equivalent
PO_4 = Phosphate
Sb-e = Antimony equivalent

Several other missing indicators that are not in TRACI are being considered in future LCA impact indicator systems. These include a noise indicator, which in is particularly important for airports. Ongel [142] suggested a method for including the environmental effects of noise in road LCAs. There is also an effort underway to develop social and economic impact categories and indicators. The United Nations Environment Programme [143] published guidelines in 2009 for social and socioeconomic LCAs of products in which impact categories such as health and safety, working conditions, human rights, socioeconomic repercussions, etc., are suggested. These may be of interest to the FAA for future use in LCA studies.

The goal and scope of the study defines which indicators to select. It is also possible to select both mid- and endpoint indicators together in an LCIA. The ReCiPe [140] and IMPACT 2002+ [144] systems are examples of existing methodologies that combine both mid- and endpoint indicators. It should be noted that the indicators may not be the same for different methodologies. Results should not be summed across impact categories because the units of LCIA results are different for different impact categories.

5.5 LIMITATIONS OF LCIA.

The uncertainties, data gaps, and cut-offs in the LCI phase may be introduced in the LCIA results. "Value-choices, exclusion of spatial and temporal, threshold and dose-response information, relative approach, and the variation in precision among impact categories" are some of the examples of LCIA limitations stated in ISO 14044 [6]. The site-specific locations where the impacts occur are generally not accounted for (i.e., emissions are independent of where they occur). Emissions occurring in a more populated area such as a city will have more detrimental effects on human health than when they occur in an unpopulated area, and the impacts of waste and resource use may be relative to where they occur.

Characterization modeling and factors have uncertainties as well. In a study by the Joint Research Centre of the European Commission [62] on identifying the best existing practice for characterization modeling in LCIA, it was found that characterization modeling has improved in recent years, especially at the midpoint level. However, in the last decade, it was discovered that characterization factors often differ between the models used in different impact indicator systems for the same substance and impact. Likewise, combined midpoint and endpoint level characterization modeling also needs further development [62].

In LCIA, there is also a lack of consideration of when the impacts are occurring in a life cycle. Currently, GHG emissions are summed in an LCA study and GWP is calculated for the time horizon of 100 years. This means that the global warming effects of emissions that occur in 2016 will have the same effects in year 2115, which is not necessarily scientifically valid. It is expected that these limitations in indicator calculation will be improved as research continues. For example, the issues regarding when GHG emissions occur was corrected with a time-based model by Kendall [145].

5.6 THE LCIA FOR COMPARATIVE ASSERTIONS TO BE DISCLOSED TO THE PUBLIC.

A sufficiently comprehensive set of category indicators should be used in an LCIA for comparative assertions that will be disclosed to the public. ISO 14044 [6] states "The comparison shall be conducted category indicator by category indicator." It is further stated that category indicators should "as a minimum" be:

- scientifically and technically valid, i.e., using a distinct identifiable environmental mechanism and/or reproducible empirical observation, and

- environmentally relevant, i.e., have sufficiently clear links to the category endpoint(s) including, but not limited to, spatial and temporal characteristics. [6]

As a result, category indicators have to be internationally accepted. Weighting (optional element in LCIA, see section 5.2), being an unscientific approach, cannot be used in comparative assertions intended to be disclosed to the public.

6. INTERPRETATION.

Interpretation is the final technical phase in an LCA study before critical review and reporting, and consists of the following tasks [6]:

- 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) goal and scope, inventory analysis, and the impact assessment

- Development of conclusions, a statement of limitations, and recommendations

The EN 15804 standard requirements for the interpretation phase stipulate that it consider [12]:

- 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. 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.

The interpretation methodology should be clearly described in the scope definition phase [6]. ISO 14044 states that the most important aim of LCA studies is that they be reported transparently so readers can appreciate the goals and scope of the study and the conclusions and recommendations drawn from it [6].

Interpretation is an iterative process, both within its own stage 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 the calculation of impact indicators.

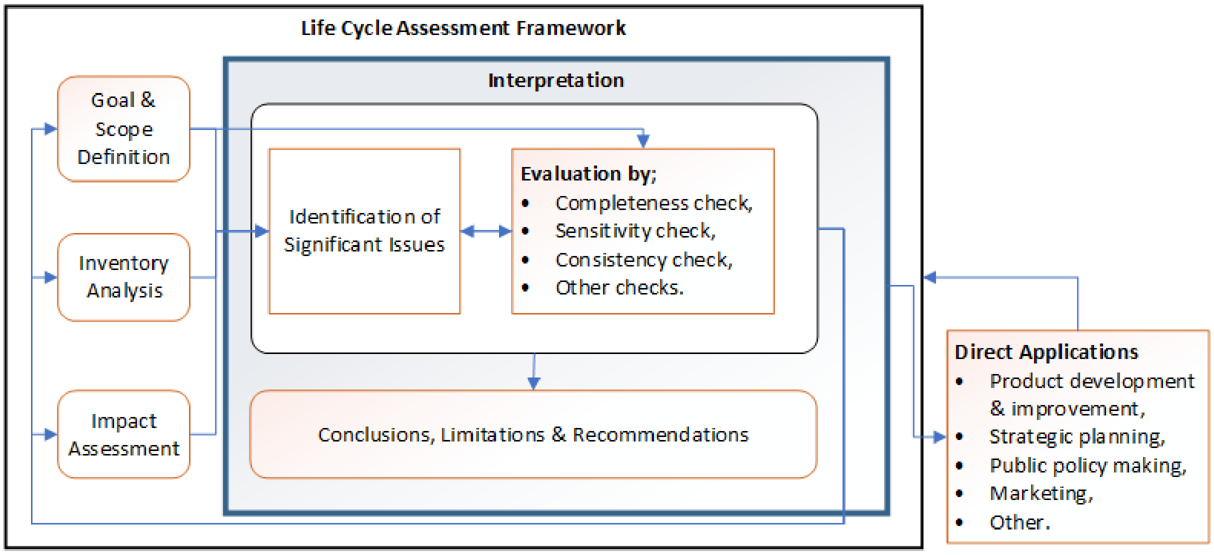


Figure 18. Relationship Between Interpretation Phase Elements and Other LCA Phases

Different levels of complexity can be used in the LCA, including benchmarking studies, LCA studies with a small set of impact indicators, and LCA studies with a full set of indicators. The process for the interpretation phase shown in figure 19 applies to each of these use cases and all levels of complexity.

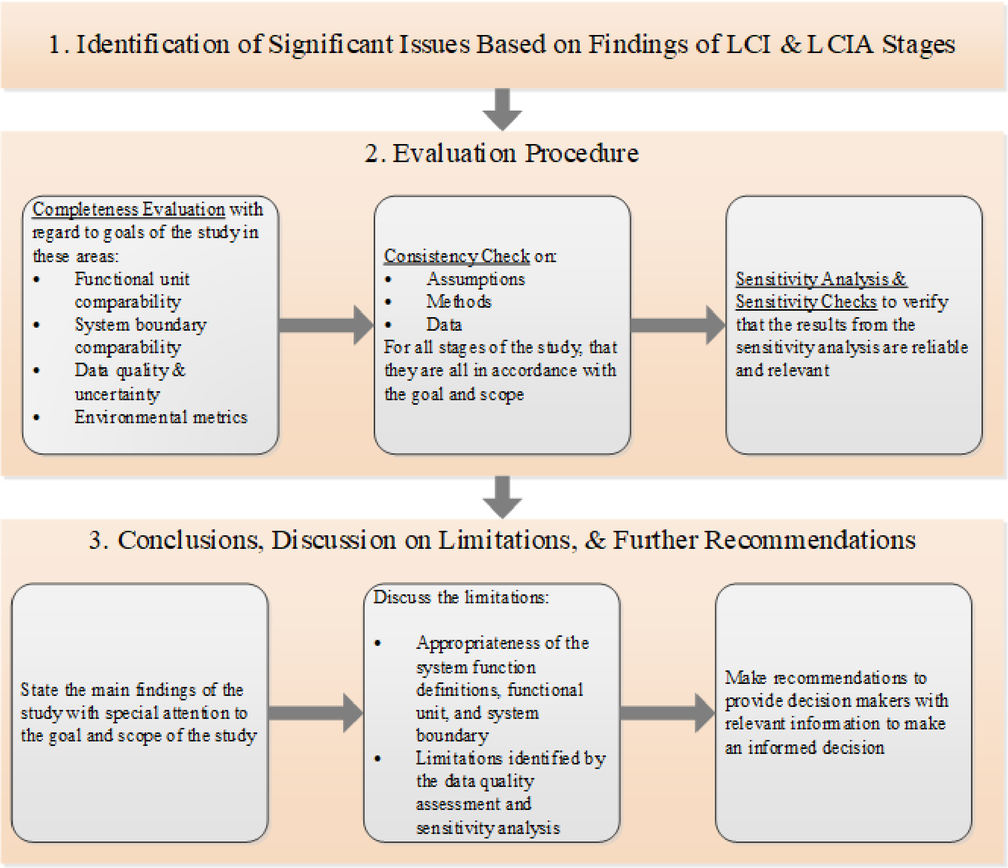


Figure 19. Process for Conducting the Interpretation Phase of an LCA Study

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

6.1 IDENTIFICATION OF SIGNIFICANT ISSUES BASED ON FINDINGS OF LCI AND LCIA PHASES.

As the first step in the interpretation phase, findings of the LCI and LCIA of the study 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 indicate potential environmental impacts and not the actual impact on the category endpoint, nor safety margins and the risks involved [6].

The organization of the LCI and LCIA information should make use of graphics and summary tables to help point out areas where highest impacts exist. The information should be presented in such a way that it allows decision-makers to interpret the results and to identify critical areas on which to focus. The information can be organized in tables or graphics by the following types of elements, among others [6]:

- 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 [6]:

- Contribution analysis, in which the contribution of life cycle stages or groups of processes to the total result are examined, for example, by expressing the contribution as a percent 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 airfield infrastructure 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 stages with the largest impact. Individual processes within each stage should generally also be shown, which may be further broken down by flows if needed to meet the goal of the study.

6.2 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.

6.2.1 Completeness.

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

Completeness should be checked by first verifying whether the scope identified for the LCI and LCIA phases was met. If not, then the missing or incomplete scope should be completed. If the missing or incomplete LCI and/or LCIA scope cannot be completed, then the necessity of such information for satisfying the goal and scope of the LCA should be considered. The findings from the completeness check and the justification for not completing the original LCI and/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 20 [19].

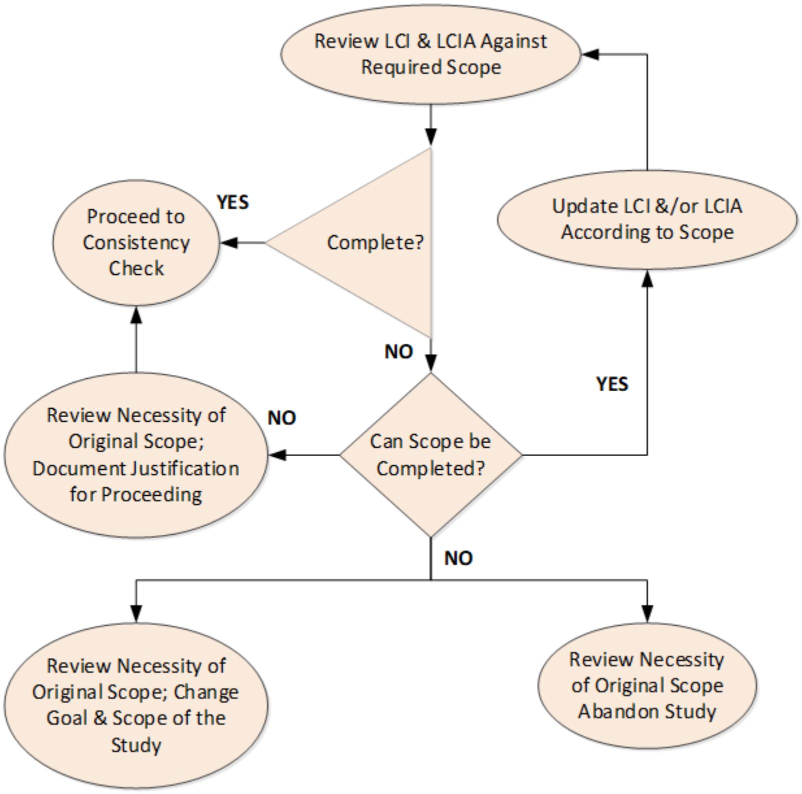


Figure 20. Completeness Evaluation Process

6.2.2 Consistency.

Consistency checks are conducted to verify that consistent assumptions, methods, and data used throughout different stages 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 20 for the completeness check, 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 possible to move forward with the available information, whether it is necessary to perform additional work in the LCI or LCIA phases, or whether to change the goal of the study and update the scoping document, or abandon the study.

Currently, consistency checks for airfield infrastructure LCA studies often encounter problems with the availability of specific LCI data as opposed to generic data or, sometimes, with a lack of data or a 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 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 airfield infrastructure 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.

Problems with the appropriateness of the impact assessment methods may arise when specific local impacts are of interest, but the chosen impact assessment methods are less granular and sometimes summarize impacts occurring in different places as if they are all occurring in the place of interest.

6.2.3 Sensitivity Analysis Check and Consideration of Uncertainty.

Sensitivity checks are done to verify that the results from sensitivity analysis are reliable and relevant for making conclusions and providing recommendations. Sensitivity analysis 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 (i.e., LCI, LCIA). In other words, consideration should be given to [6]:

- 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 an airfield infrastructure LCA is intended to be used in comparative analysis with 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 20 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 or the results from the phases of the study should be assessed to determine whether it is possible to move forward with the available information, whether it is necessary to perform additional work in the LCI or LCIA phases, or whether to change the goal of the study and update the scoping document, or abandon the study.

If the sensitivity check shows that the sensitivity analyses were 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.

Variability exists in how to deal with uncertainty and how relevant it is for specific LCA studies. This section includes examples of types of uncertainty that are dealt with in literature around LCA and uncertainty, and ends with examples of how uncertainty is dealt with and reported in LCA studies. It is recommended to review this section and to assess the relevant parts for a specific study at hand.

In general, uncertainty can be divided into three categories, as shown in figure 21 (adapted from reference 146), lack of knowledge, variability in the data (due to heterogeneity across time, space or individuals), and decision uncertainty.

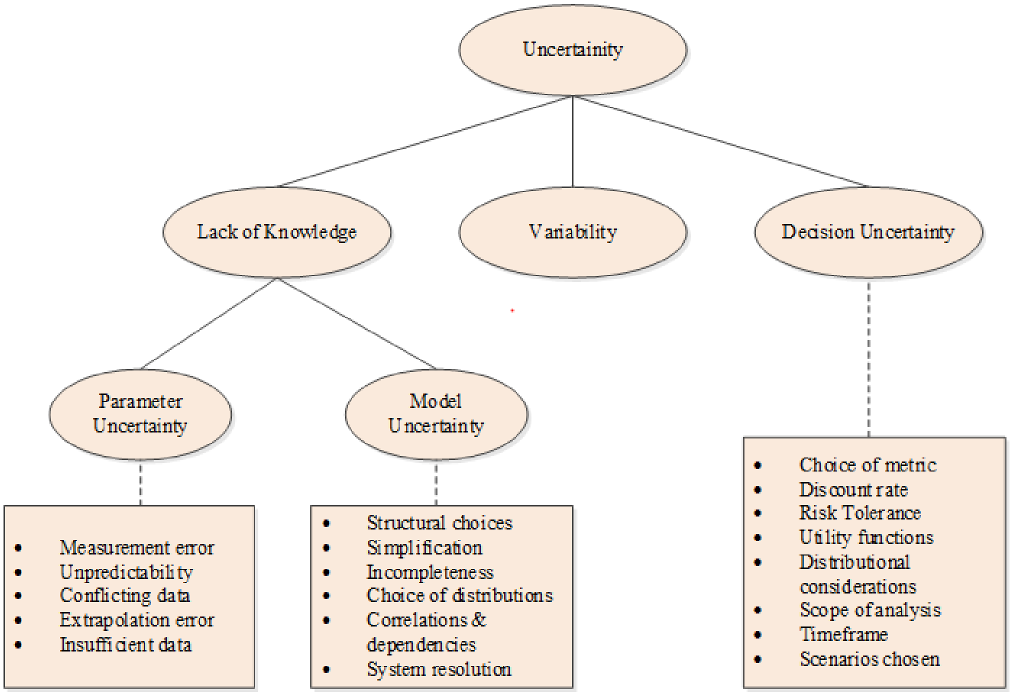


Figure 21. Types of Uncertainty

From another perspective, the GHG Protocol [147] divides uncertainty into three groups: parameter uncertainty, scenario uncertainty, and model uncertainty. 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 EOL assumptions. Model uncertainty is produced when outcomes from inaccurate models do not represent the real world.

Baker and Lepech [148] list the 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

6.3 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 so that the recommendations will provide decision-makers with relevant information to make an informed decision. The limitations in any stage of the study that is 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

The interpretation phase should use a systematic approach in presenting the findings to meet the study requirements 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 they 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.

Future trends in LCA will likely influence the global harmonization of LCA approaches and the comprehensiveness of interpretation for all types of civil infrastructure such as the following [53]: new tendencies and expansions of classic LCA including, social LCA (S-LCA); triple-bottom line sustainability assessment (3-E; Environment, Economic and Social Equity), life-cycle sustainability assessment (LCSA); real-time and dynamic LCA; LCA for territories and organizations, and planetary boundaries.

7. REPORTING AND CRITICAL REVIEW.

7.1 REPORTING.

According to ISO 14044 [6], the data, methods, assumptions, results, conclusions, and limitations should be complete, accurate, and transparently presented with a sufficient level of detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA without being biased to the intended audience. The report content and format should be consistent with the goal and scope identified at the beginning of the study. Any changes made to the study goal and scope should be reported to explain the iterative process.

Some key items to consider in developing the reporting requirements for the document include the following:

- Introduction—This section should include the background of the study, literature review, gap identification, and motivation for the LCA.
- LCA-Related Elements—This section includes general aspects such as LCA commissioner/audience/practitioner, goal and scope elements, inventory analysis, impact assessment, results, interpretation, and critical review.
- Additional Information—This section consists of any additional requirements for comparative LCA studies to be disclosed to the public.

If an LCA contains confidential information, a third-party review may be requested. The information can be documented in a separate confidential report that is reviewed by critical reviewers under confidentiality. This information does not have to be made available externally.

7.2 CRITICAL REVIEW.

7.2.1 Deciding Whether a Critical Review is Needed.

The determination as to whether a critical review should be performed is decided during the scoping of the study. A 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. A critical review is likely not needed if the study results are to be informally used for internal purposes such as internal benchmarking for efficiency improvement at a pavement materials plant, internal evaluation of a contractor’s construction operations, or for scoping estimates prior to initiating a formal LCA.

As part of the initial scoping, it should be determined whether the reviewers are internal or external to the organization performing the LCA and whether it is a comparative study. Confidentiality agreements with reviewers regarding the content of the LCA should be created as needed.

The critical review process and mandate for the reviewers of the LCA study should be documented in the scoping of the LCA, including the type of critical review and the names of the critical reviewers. The type and format of the critical review report for the LCA should be based on the goal and the audience for the study, and should be included in the scoping document. The steps in the critical review determination process based on ISO 14044 [6] are shown in figure 22.

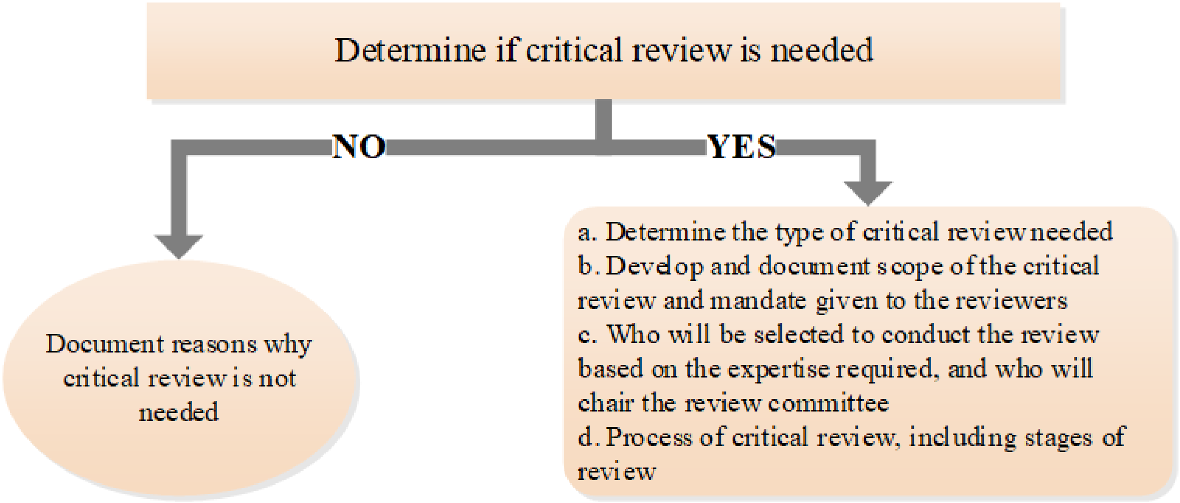


Figure 22. Critical Review Determination Process

7.2.2 Selection of Critical Reviewers.

Selection of appropriate critical reviewers is important, especially for studies that require external reviewers. ISO requires that the critical review team include persons with LCA expertise and domain expertise, or both. The acceptance of the conclusions and recommendations of the LCA study by its readers will depend in part on the expertise of the critical reviewers.

There are currently no processes for independent certification of the qualifications of critical reviewers, which makes it important that appropriate consideration be given to the selection of the review team on a case-by-case basis.

7.2.3 Elements of Critical Review.

The critical review evaluates how the LCA is conducted and whether it addresses the stated goals. It also evaluates the scientific rigor as well as the data and methodology used throughout the study. Critical reviews improve reliability of the results and will likely increase the efficiency of data collection if they are conducted several times during the development of the LCA study: after the scoping of the study, then after data collection, and then after the conclusions are drafted [149].

According to ISO 14044 [6], the critical review process should include review of the following elements:

- the methods used to implement the LCA are consistent with the standards identified in the goal and scope,

- the methods used to perform the LCA study 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, and

- the report is transparent and consistent.

7.2.4 Reporting of Critical Review and Response.

The critical review should report the analysis of the methodological and technical aspects of the LCA study under review. The expert panel should review the reasonableness of the findings and interpretation of the study results. The report should also include the names and affiliations of reviewers, critical review reports/statements, and responses by the authors to the comments and recommendations made by the reviewers.

An example of columns in a table used for critical review is shown in table 13. The reviewers should document each comment in rows underneath the column headings.

Table 13. Critical Review Table

Comment Number (preface with T for technical, E for editorial, G for general)	Section	Page and table or figure number if applicable	Comment	Recommendation	Response	Resolved?
T	5.1	Figure 16	XXX	XXX	XXX	XXX

8. AIRFIELD LCA CASE STUDIES.

8.1 CASE STUDIES OBJECTIVES.

To demonstrate use of LCA guidelines and framework that were developed in this project, several airports were contacted across the U.S. and a number of possible case studies were discussed based on the completed or ongoing projects at the airports. Four airports were selected for case studies based on their ability to provide information for the case study topics of their choice. A shared interest of these airports was in being able to quantify the environmental benefits from using different asphalt and concrete additives, and in using recyclable materials that reduce the use of new natural resources and energy, potentially reducing emissions. The airports also showed interest in being able to quantify the environmental impacts of different design alternatives, projects, and material designs for decision support. The following case studies from four different airports in the U.S. were selected:

- Use of warm-mix asphalt (WMA) by John F. Kennedy International Airport (JFK) in cooperation with the Port Authority of New York and New Jersey (PANYNJ)

- Use of WMA and use of concrete mixes with recycled materials by Chicago O'Hare International Airport (ORD) in cooperation with Bowman, Barrett & Associates Inc. (BBANDAINC)

- Use of WMA and RAP by Boston Logan International Airport (BOS) in cooperation with the Massachusetts Port Authority (Massport)

- Comparison of alternative pavement designs by Nashville International Airport (BNA) in cooperation with Atkins (consultants).

8.2 ASSUMPTIONS AND DATA USED FOR ALL CASE STUDIES.

A few assumptions and some common data were used in executing all of the case studies. Where data were unavailable, data and LCIs collected by UCPRC were used for the case studies [136].

For electrical energy, the electricity mix generation data for each U. S. state were gathered from the U.S. Energy Information Administration (EIA) [150]. The particular electricity mixes were used for modeling electricity impacts in GaBi [151] (LCI and impact assessment software) for different materials and processes for each airport using common information for each source of electrical energy.

Table 14 shows the fuel and natural gas LCIAs and PEDs that were used to prepare impact assessments for the materials and construction stages in all the case studies. Table 15 shows the transportation impacts used in all the case studies for a functional unit of 1000 kg-km of materials being transported. A national average mixing temperature for HMA of 350°F was used to determine the environmental impacts from the production of HMA, and a linear extrapolation was done based on their respective mixing temperatures to determine the environmental impacts of WMA and polymer-modified asphalt mixes for the different case studies. Some of the other LCIAs that were common for all the case studies are presented in table 16 (materials) and table 17 (construction). The impact of construction activities for each pavement treatment is calculated by estimating total fuel consumption for 1 ln-mile of the road by considering the equipment used, engine horsepower and fuel efficiency, and number of passes needed (table 17).

The following impact indicators were calculated for the case studies:

- GWP

- POCP

- Atmospheric particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$)

- PED from nonrenewable sources consumed as energy (PED-NR)

- PED from renewable sources consumed as energy (PED-R)

- PED for materials made from energy sources not consumed as energy (PED-FS), including both renewable and nonrenewable sources, also called feedstock energy; none of the energy sources used as materials in these case studies were renewable, with all the feedstock energy being related to petroleum-based products.

The first three indicators for all the case studies were selected from the TRACI [138] set of impact indicator models. POCP and $PM_{2.5}$ are two of the major impacts that affect human health and quality of life in urban areas, whereas GWP is a global issue. The locations of the POCP and $PM_{2.5}$ emissions are summed across all emission locations in the system. The division of PED into three parts was adapted and simplified from the European EN 15804 [12] approach that is also recommended in the FHWA pavement LCA framework [19]. It was assumed for this study that all asphalt mixing plants are using natural gas, which may not be true because fuel oil is used in some parts of the U.S. It was also assumed that the use of fuel oil would generally be prohibited or otherwise considered unacceptable in urban areas near where major airports are located.

The allocation method used for recycled or reclaimed materials, such as RAP, was the cut-off approach. This means that the impacts of producing the material that will be recycled in the project of interest are attributed to the previous project, and only the impacts of processing and transporting the material for the current project are included in the impact analysis.

Table 14. Impacts of Non-Electricity Energy Sources

Item	GWP (kg CO_2-e)	POCP (kg O_3-e)	$PM_{2.5}$ (kg)	PED-NR (MJ)	PED-R (MJ)	PED-FS (MJ)
Diesel, burned in equipment (1 gal)	1.19E+01	5.27E+00	9.37E-03	1.65E+02	0.00E+00	0.00E+00
Natural gas, combusted (1 m^3)	2.41E+00	5.30E-02	1.31E-03	3.84E+01	0.00E+00	0.00E+00

Table 15. Transportation Impacts for a Functional Unit of 1000 kg-km

Item	GWP (kg CO_2-e)	POCP (kg O_3-e)	$PM_{2.5}$ (kg)	PED-NR (MJ)	PED-R (MJ)	PED-FS (MJ)
Transport w. Heavy Truck 24 Tonne	7.8E-02	1.2E-02	2.5E-05	1.1E+00	0.00E+00	0.00E+00

Table 16. Materials Impacts for a Functional Unit of 1000 kg

Item	GWP (kg CO_2-e)	POCP (kg O_3-e)	$PM_{2.5}$ (kg)	PED-NR (MJ)	PED-R (MJ)	PED-FS (MJ)
Limestone	4.44E-03	2.11E-04	8.24E-08	6.80E-02	1.04E-02	0.00E+00
Paraffin (wax)	1.37E+00	7.57E-02	4.70E-04	5.43E+01	2.70E-01	0.00E+00
PCC admixture, air entrainer	2.66E+00	8.68E+00	2.55E-03	2.10E+00	0.00E+00	0.00E+00
PCC admixture, retarder	2.31E-01	4.23E-02	9.81E-05	1.57E+01	0.00E+00	0.00E+00
PCC, with 50% slag	4.45E-01	1.76E-02	1.23E-04	2.56E+00	0.00E+00	0.00E+00
RAP	7.16E-03	1.39E-03	2.70E-06	1.02E-01	0.00E+00	0.00E+00
Quicklime	1.40E+00	3.52E-02	7.11E-04	7.88E+00	0.00E+00	0.00E+00
Styrene-butadiene rubber (SBR)	4.13E+00	1.29E-01	4.48E-04	1.02E+02	9.00E-01	0.00E+00

Table 17. Construction Impacts for 1 lane-km of Surface Treatment

Item	GWP (kg CO_2-e)	POCP (kg O_3-e)	$PM_{2.5}$ (kg)	PED-NR (MJ)	PED-R (MJ)	PED-FS (MJ)]
Aggregate Base	3.2E+03	1.4E+03	2.5E+00	4.4E+04	0.00E+00	0.00E+00
HMA (Mill & Fill)	3.4E+03	1.5E+03	2.7E+00	4.7E+04	0.00E+00	0.00E+00
HMA (Overlay)	2.1E+03	9.2E+02	1.6E+00	2.9E+04	0.00E+00	0.00E+00
PCC	1.8E+03	8.1E+02	1.4E+00	2.5E+04	0.00E+00	0.00E+00

8.3 JOHN F. KENNEDY INTERNATIONAL AIRPORT.

8.3.1 Goal and Scope.

A recently completed (2015) runway reconstruction project at JFK airport consisted primarily of the removal and reconstruction of the runway 4R-22L. Shoulder and erosion pavements were also reconstructed. The airport was interested in quantifying the environmental impacts of the WMA that was used in the surface mix of the shoulder and erosion pavements and comparing them with impacts resulting from the use of HMA. The goal defined for the case study after discussion with the PANYNJ was to quantify the environmental impacts from the material production and construction of the different layers of the erosion and shoulder pavements. This is an example of a standalone or benchmark study. A few example questions that can be answered from this study include:

- What are the total environmental impacts from this project in terms of energy, resource use, and emissions to air, water, and land?
- What are the typical construction environmental loads that arise from a WMA project?
- Which processes are most energy intense and/or emit most emissions?

As the reconstruction of the runway was recently completed, the scope of the study was limited to cradle-to-lay, in which the materials and construction stages of the life cycle of the pavements, in addition to transportation of materials from one location to another, were considered. The functional unit defined for the case study was construction of 10 ft long and 5 ft wide erosion and shoulder pavements for a nominal design life. Setting such a functional unit is also a good example for pavements that have varying widths or thicknesses and could also be used for airside vehicle roads, shoulders, drainages, and aprons, as discussed in the guidelines.

8.3.2 The LCI and LCIA.

PANYNJ shared a number of runway reconstruction project-related documents from which data and information relevant to the case study were extracted. The pavement cross-section designs for the shoulder and erosion pavements were extracted from the project drawings as shown in figure 23. The WMA mix design that was used for the construction of the surface layer of the pavements being considered was extracted from the job mix formula (JMF) document and is presented along with other layer designs that include macadam and dense graded aggregate base as shown in table 18. The material producers' information, material production plant, and quarry locations were also collected from the documents and average material transport distances (in miles) between different facilities were determined using Google Maps™, as shown in table 19. The asphalt mixing plant was in Flushing, New York.

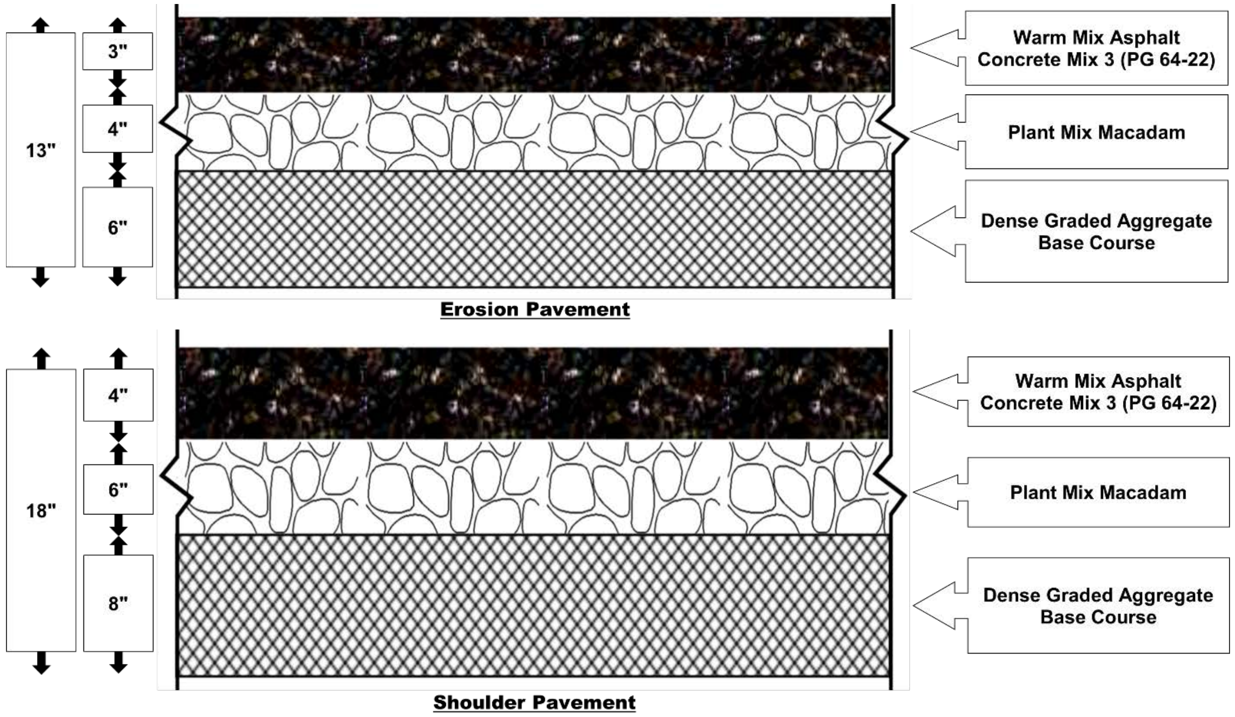


Figure 23. Cross-Section Thicknesses of the Erosion and Shoulder Pavements' Different Layers

Table 18. The WMA and Macadam Design for Both Shoulder and Erosion Pavements

Mix Type	Materials	Type	Mix Design (%)
WMA mix 3	Asphalt binder	PG64-22	5.3
	Additive	Evotherm™ 3G	0.5
	Aggregate	-	94.7
Macadam	Asphalt binder	-	2.7
	Plant mix macadam	1″, 3/4″, 3/8″ and #4	97.3
Densely graded aggregate base course	Aggregates	-	100

Table 19. Different Material Production Facilities and Estimated Transport Distances

Material	Producer	Location		Distance (Miles)
		From	To	
Crushed aggregate	Tilcon New York Inc.	Mt. Hope, NJ	Flushing, NY	60
Crushed aggregate	Tilcon New York Inc.	Mt. Hope, NJ	JFK, NY	65
Asphalt mixture	Willets Point Asphalt Corp.	Flushing, NY	JFK, NY	10
Binder	NJ asphalt terminals	Elizabeth, NJ	Flushing, NY	45
Evotherm™ 3G	MWV Specialty Chemicals	North Charleston, SC	Flushing, NY	765
Macadam mix		Flushing, NY	JFK, NY	10

Table 20 presents the 2015 electricity generation from different resources (also called electricity mix design) for New York [150] that was used to calculate the impacts of materials and construction for this case study. Primary energy (from renewable and nonrenewable sources) and the EPA's TRACI indicators were selected for the LCIA. Using the inventory data from table 20, the energy and emissions to produce 1 MJ of electric energy were determined. The total energy consumed (combination of the primary energy from renewable and nonrenewable resources) and the TRACI results are presented in table 21.

Table 20. Average Electricity Mix of New York (2015)

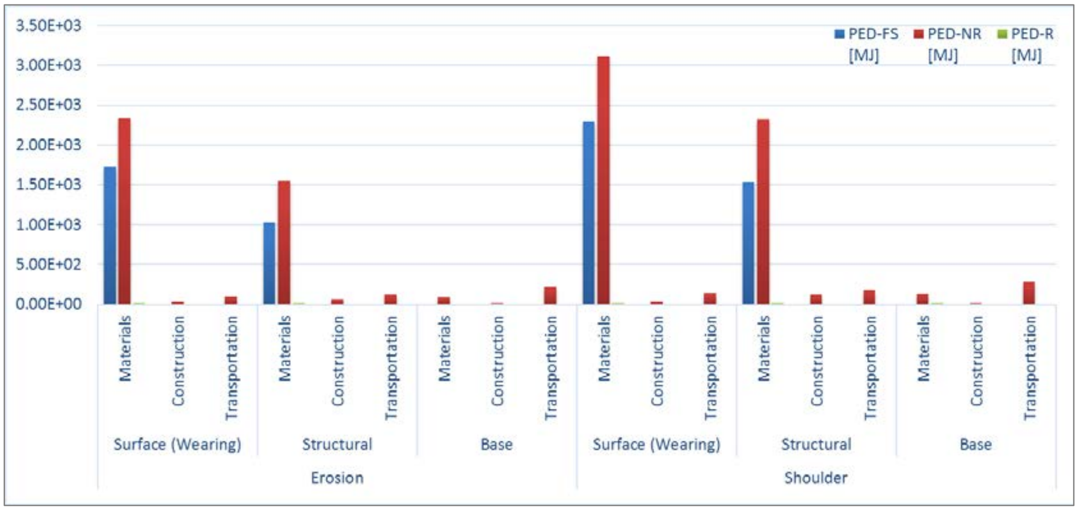
Energy Source	Electricity Mix(%)
Coal	1.71
Hydroelectric Conventional	18.71
Natural Gas	40.94
Nuclear	32.08
Other Gases	0.00
Other	0.66
Petroleum	1.36
Other Biomass	1.17
Solar Thermal and Photovoltaic	0.07
Wind	2.86
Wood and Wood Derived Fuels	0.44
Total	100

Table 21. Energy Consumption and Environmental Impacts of Electricity Generation in New York (2015)

Item	Acronym	Unit	Description	Value
Use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials	PED-NR	MJ	Energy from nonrenewable sources that was consumed as fuel and is not available anymore as stored energy in materials	2.25E+00
Use of nonrenewable primary energy resources used as raw materials (feedstock energy)	PED-FS	MJ	Energy from nonrenewable sources that is still available as stored energy in materials	0.00E+00
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PED-R	MJ	Total energy from renewable sources	4.00E-01
Global warming potential, including biogenic carbon, including LUC, no norm/weight	GWP	kg CO_2-e		7.80E-02
Human health: criteria air pollutants	$PM_{2.5}$	Kg	Exposure to elevated $PM_{2.5}$	7.25E-06
Photochemical ozone creation potential	POCP	kg O_3-e	Potential to cause photochemical smog	1.16E-10

Note: Functional unit is 1 MJ of electricity delivered on site.

UCPRC material and construction equipment LCIs were used for the case study in case of data unavailability from the project [136]. Evotherm™ 3G production data was unavailable, thus production energy and emissions for fatty acid lubricants were used for this material. WMA was produced at 260°F, whereas plant-mixed asphalt macadam was assumed to be produced at an HMA mix temperature of 320°F. The results for the impact calculations are presented in figures 24 and 25, and table 22.



Note: PED-FS is feedstock energy in materials made from petroleum; this energy was not consumed.

Figure 24. Consumed Energy per Life Cycle Stage per Structure Type

Table 22. Final Results for Each Stage per Layer and Structure Type

Pavement	Layer	Life Cycle Stage	Percent of Total					
			GWP	POCP	$PM_{2.5}$	PED-NR	PED-R	PED-FS
Erosion	Surface (Wearing)	Materials	13%	11%	16%	21%	17%	26%
		Construction	1%	2%	1%	0%	0%	0%
		Transportation	2%	2%	1%	1%	0%	0%
		TOTAL	17%	16%	19%	23%	17%	26%
	Structural	Materials	13%	10%	14%	14%	14%	16%
		Construction	1%	4%	2%	1%	0%	0%
		Transportation	3%	3%	2%	1%	0%	0%
		TOTAL	18%	17%	17%	16%	14%	16%
	Base	Materials	2%	2%	2%	1%	10%	0%
		Construction	0%	1%	1%	0%	0%	0%
		Transportation	5%	5%	3%	2%	0%	0%
		TOTAL	7%	8%	5%	3%	10%	0%
Shoulder	Surface (Wearing)	Materials	18%	15%	21%	29%	23%	35%
		Construction	1%	2%	1%	0%	0%	0%
		Transportation	3%	3%	2%	1%	0%	0%
		TOTAL	22%	21%	25%	30%	23%	35%
	Structural	Materials	20%	15%	21%	21%	22%	23%
		Construction	3%	8%	4%	1%	0%	0%
		Transportation	4%	4%	3%	2%	0%	0%
		TOTAL	27%	27%	27%	24%	22%	23%
	Base	Materials	2%	3%	2%	1%	14%	0%
		Construction	0%	1%	1%	0%	0%	0%
		Transportation	7%	7%	4%	3%	0%	0%
		TOTAL	10%	11%	7%	4%	14%	0%
TOTAL for the Functional Unit			2.89E+02	4.79E+01	1.57E-01	1.08E+04	8.15E+01	6.57E+03
			(kg CO_2-e)	(kg O_3-e)	(kg)	(MJ)]	(MJ)	(MJ)

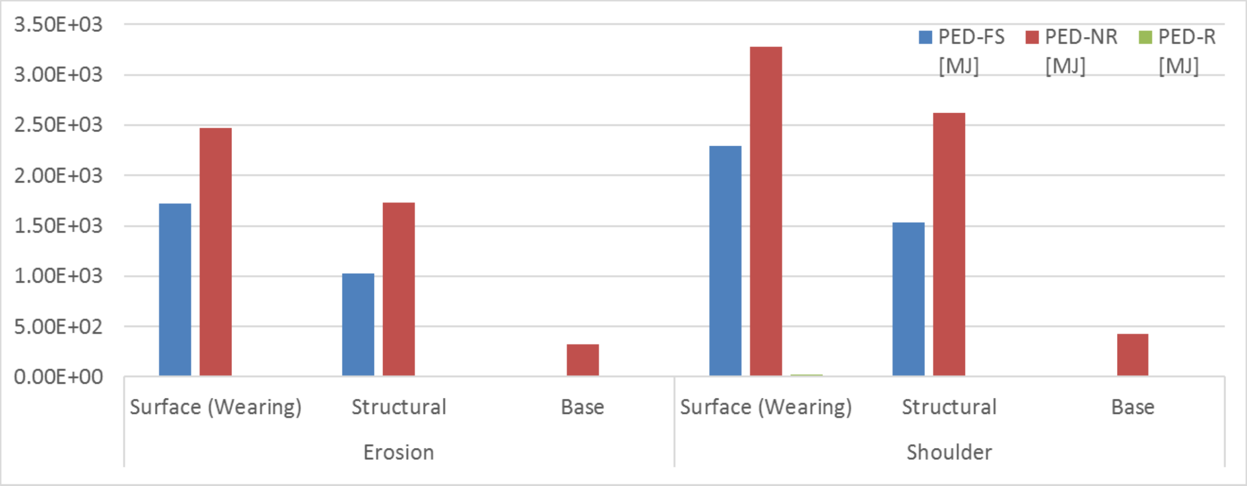


Figure 25. Primary Energy Demands for Each Layer per Structure Type

8.3.3 Interpretation.

The shoulder pavement had a higher set of environment impact contributions than the erosion pavement due to thicker pavement section. They used the same materials, so there were not any differences in impact due to the materials themselves. In this analysis, the materials stage can be considered as the hot spot, meaning that improvement of the material production techniques will likely lead to the largest improvement in resource use, which is higher for the materials stage than the transportation and construction stages. Differences between the materials used are clearly visible. The use of asphalt binder and the heating of the aggregates and asphalt for mixing make a large contribution to the impacts compared with the unstabilized aggregate base. A reduction in environmental impacts from material production can also be achieved by an increase in the use of recyclable materials. This reduces the extraction, processing, and transportation of raw materials, thus resulting in far lower impacts on the environment. This may be offset at least partly by the higher mixing temperatures needed when using greater quantities of RAP. Transportation for the aggregate base is of secondary importance to the materials, but it does contribute 12% GWP and 5% PED-NR. Very long transport distances using trucks—as opposed to rail or barge or on-site recycling—may also increase the environmental impacts; this was shown by other authors in their sensitivity analyses where transportation of material becomes the most energy-intense process in the life cycle of a pavement [61].

8.4 CHICAGO O’HARE INTERNATIONAL AIRPORT.

8.4.1 Goal and Scope.

The FAA and U.S. airports have shown interest in innovations that lead to use of recyclable materials and incorporating other practices in their daily activities to reduce the use of new materials. Although these changes have been popular in highway practice, the differences in safety requirements and differences in loading between airfields and highways must be considered. ORD and other airports, as well as the FAA, are also interested in investigating the potential environmental benefits of using WMA and concrete mixes with SCMs and reduced cement content. After several discussions with BBANDAINC, the consultants for different projects at ORD, the goal selected for the case study was to determine the benefits of using:

- WMA with reclaimed materials as surface mix versus conventional HMA P-401.
- Concrete mixes with SCMs and reduced cement content, versus conventional concrete mix P-501.

This is an example of a comparative LCA study. A decision was made that the scope of this study would be cradle-to-gate plus transportation, which means that it would consider both the materials stage and the transportation of materials, such as their transport from their source to the production plant, or from the material storage facility to the mixing plant. The construction stage was assumed to be the same and was not considered. The functional unit was defined as 1 tonne of material produced at the production plant.

8.4.2 The LCI and LCIA.

BBANDAINC was asked to share the mix designs of asphalt and concrete that were used for construction at ORD. BBANDAINC shared JMFs for the WMA containing reclaimed materials, conventional HMA P-401, modified concrete mix and conventional concrete mix P-501. The data extracted from these documents included information about the materials, the mix designs, the material producers, and the HMA and concrete production plant and quarry locations. This information and average material transport distances between different facilities were determined using Google Maps™, and are reported in tables 23 and 24, respectively. It is assumed that the loaded truck brings the materials to the facility and then returns empty. The transportation energy and emissions reported for each material for both directions are allocated to a single trip.

Table 23. Different Material Mixes and Their Designs

Mix Type	Materials	Type/Specifications	Design	Units	Comments
WMA	Asphalt binder	PG 46-34 (virgin)	3.22	% by weight of asphalt mixture	Total asphalt binder = 6.14%
	RAP	Binder	1.88	% by weight of asphalt mixture	-
	Rubber	Ground tire rubber (GTR)	0.74	% by weight of asphalt mixture	12% by weight of asphalt binder
	Additive	Evoflex™	0.31	% by weight of asphalt mixture	5% by weight of asphalt binder
	RAS	#2 size	5.63	% by weight of asphalt mixture	6% by weight of aggregate
	Mineral filler		3.75	% by weight of asphalt mixture	4% by weight of aggregate
	Crushed aggregate	#7, #5, #2 (virgin)	84.47	% by weight of asphalt mixture	Total aggregate = 93.86%
Conventional HMA mix P-401	Asphalt binder	PG 70-28 (virgin)	5.88	% by weight of asphalt mixture	Total asphalt binder = 6%
	Polymer	Styrene butadiene styrene (SBS)	0.12	% by weight of asphalt mixture	2% by weight of asphalt binder
	Mineral filler		1.75	% by weight of asphalt mixture	1.9% by weight of aggregate
	Crushed aggregate	#6, #5, #3, #2, #1 (virgin)	90.3	% by weight of asphalt mixture	Total aggregate = 92.2%
Modified concrete mix	Cement	American Society for Testing and Materials (ASTM) C150	311	lb/cy concrete	-
	Fly ash	ASTM C618	51	lb/cy concrete	-
	Slag cement	ASTM C989	155	lb/cy concrete	-
	Crushed aggregate	ASTM C33, #4, #67, fine	3241	lb/cy concrete	-
	Water-portable	ASTM C94	220	lb/cy concrete	-
	Air entraining agent	SIKA air 260	5 to 7	%/cy concrete	-
		ASTM C260			-
	Water reducer/retarder	Plastocrete 161 (ASTM C494)	2 to 6	oz/cwt	-
Conventional concrete mix P-501	Cement	ASTM C150	352	lb/cy concrete	-
	Slag cement	ASTM C989	155	lb/cy concrete	-
	Crushed aggregate	ASTM C33, #4, #67, fine	3256	lb/cy concrete	-
	Water-portable	ASTM C94	232	lb/cy concrete	-
	Air entraining agent	ASTM C260	5 to 7	%/cy concrete	-
	Water reducer/retarder	ASTM C494	2 to 6	oz/cwt	-

Notes:
oz/cwt = Ounce to hundredweight
lb/cy = Pound per cubic yard

Table 24. Different Material Production Facilities and Estimated Transport Distances

Material	Producer	Location		Distance (Miles)
		From	To	
Crushed aggregate	Vulcan	McCook, IL	Mt. Prospect, IL	25
Air entraining agent	Sika Co.	Ottawa, IL	Rosemont, IL	80
Asphalt	Arrow Road Cons.	Mt. Prospect, IL		
Binder	Seneca Petroleum	Lemont, IL	Mt. Prospect, IL	35
Cement	Illinois Cement	LaSalle, IL	Rosemont, IL	100
Concrete	Terrell Materials	Rosemont, IL		
Evoflex™	-	-	Mt. Prospect, IL	25
Ground tire rubber	-	-	Mt. Prospect, IL	25
Reclaimed asphalt shingles (RAS)	Southwind	Bartlett, IL	Mt. Prospect, IL	25
Supplementary material 1 (slag)	Skyway Slag	Chicago, IL	Rosemont, IL	40
Supplementary material 2 (fly ash)	Head Waters	Marissa, IL	Rosemont, IL	325

Table 25 presents the 2015 electricity generation from various sources in Illinois [150]. Using the inventory data from table 25, the GaBi database was used to calculate the LCI and LCIA to produce 1 MJ of electrical energy. The total energy consumed (combination of the primary energy from renewable and nonrenewable resources) and the TRACI results are presented in table 26.

Table 25. Average Electricity Mix of Illinois (2015)

Energy Source	Electricity Mix (%)
Coal	38.04
Hydroelectric Conventional	0.06
Natural Gas	5.60
Nuclear	50.16
Other Gases	0.14
Other	0.13
Petroleum	0.03
Other Biomass	0.27
Solar Thermal and Photovoltaic	0.03
Wind	5.54
Wood and Wood Derived Fuels	0.00
Total	100

Table 26. The Energy Consumption and Environmental Impacts of Electricity Generation in Illinois (2015)

Item	Acronym	Unit	Description	Value
Use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials	PED-NR	MJ	Energy from nonrenewable sources that was consumed as fuel and is not available anymore as stored energy in materials	2.92E+00
Use of nonrenewable primary energy resources used as raw materials (feedstock energy)	PED-FS	MJ	Energy from nonrenewable sources that is still available as stored energy in materials	0.00E+00
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PED-R	MJ	Total energy from renewable sources	1.70E-01
Global warming potential, including biogenic carbon, including LUC, no norm/weight	GWP	kg CO_2-e		1.28E-01
Human health: criteria air pollutants	$PM_{2.5}$	Kg	Exposure to elevated $PM_{2.5}$	2.03E-05
Photochemical ozone creation potential	POCP	kg O_3-e	Potential to cause photochemical smog	1.82E-10

Note: Functional unit is 1 MJ of electricity delivered on site.

8.4.2.1 WMA Versus HMA.

UCPRC materials LCIs were used for the case study if data were unavailable [136]. The HMA contained polymer-modified bitumen, hence higher mixing temperatures were required. A mixing temperature of 365°F, which was reported in the JMF document, was used. For WMA, the mixing temperature was not reported in the JMF document; however, the materials specifications for the WMA mix indicated that the maximum allowed mix temperature is 340 F, so 320°F was used for the WMA. For this study, the mineral filler was assumed to be limestone. The impacts of RAP were assumed to the same for RAS. LCIA data for SBS polymer were unavailable, and therefore SBR impacts were used. It was also assumed that the ground tire rubber (GTR) used in the mix is the ground crumb rubber (GCR), hence impacts from GCR were used. The LCIA results of PED for the two cases that include the materials and transportation stages are presented in figure 26, and the emissions for the HMA and WMA are presented in table 27. The consumed PED from each constituent material in the WMA with reclaimed materials and the HMA mixes is presented in figure 27.

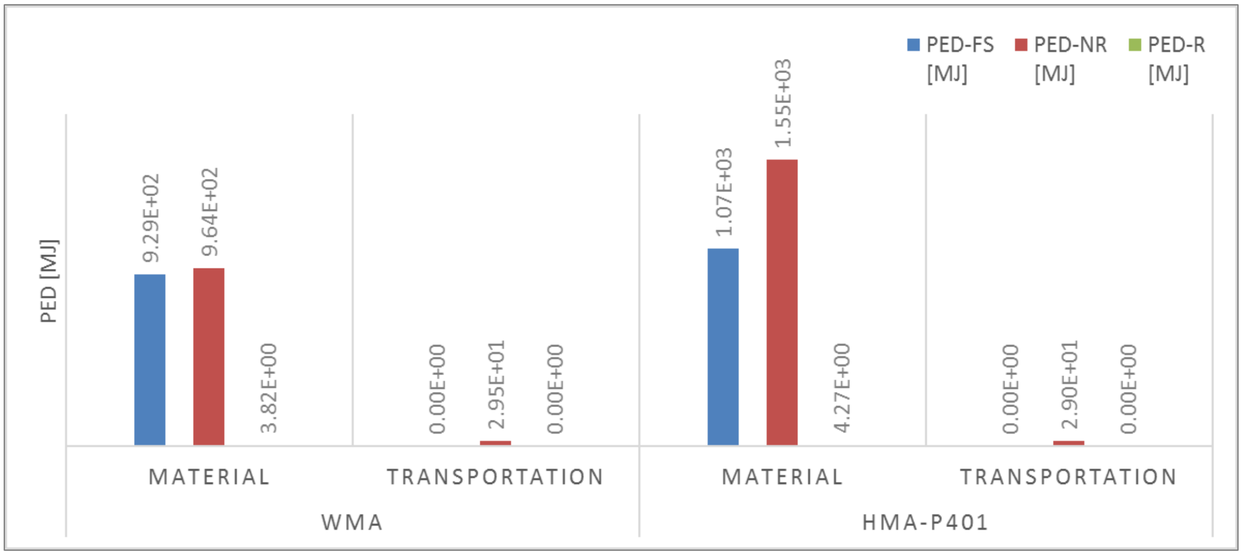


Figure 26. Cradle-to-Gate Analysis of WMA and HMA

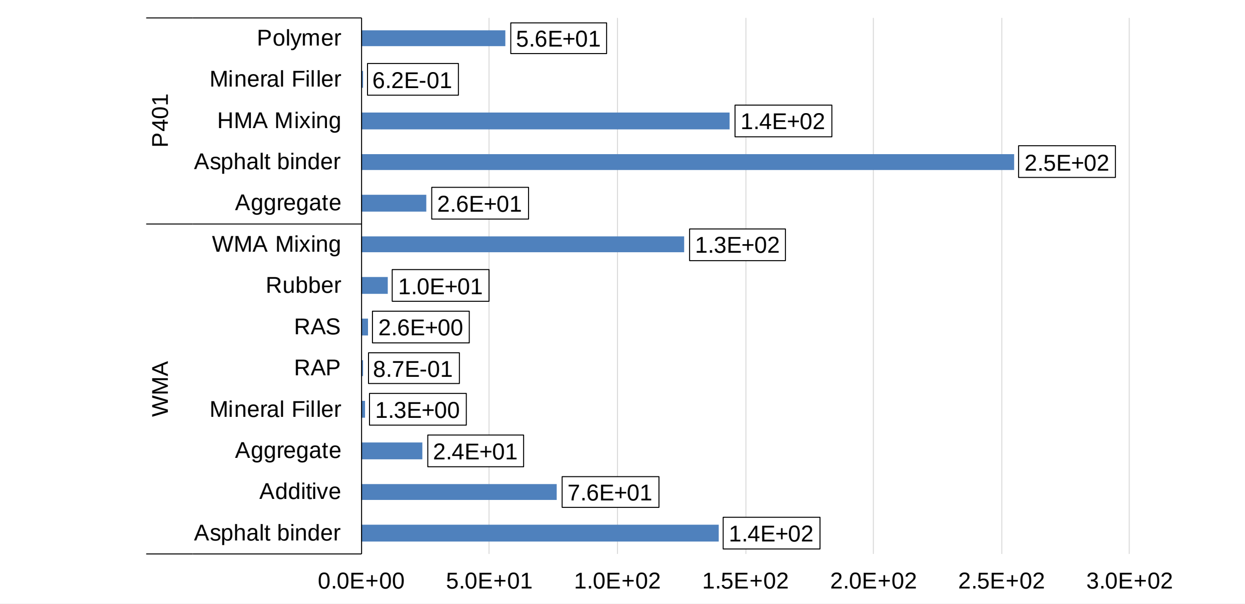


Figure 27. Consumed PED ([PED-NR] + [PED-R] – [PED-FS] in MJ) Comparison of HMA-P401 Versus WMA Materials

Table 27. Results for WMA and HMA

Mix Type	Life Cycle Stage	GWP [kg CO_2-e]	POCP [kg O_3-e]	$PM_{2.5}$ [kg]	PED-NR [MJ]	PED-R [MJ]	PED-FS [MJ]
WMA	Material	2.28E+01	2.69E+00	2.39E-02	9.64E+02	3.82E+00	9.29E+02
	Transportation	2.06E+00	3.29E-01	6.60E-04	2.95E+01	0.00E+00	0.00E+00
HMA-P401	Material	3.03E+01	3.80E+00	1.74E-02	1.55E+03	4.27E+00	1.07E+03
	Transportation	2.02E+00	3.23E-01	6.47E-04	2.90E+01	0.00E+00	0.00E+00

8.4.2.2 Concrete Versus Modified Concrete.

UCPRC materials LCIs were used for the case study where data was unavailable [136]. Slag cement was assumed to be Portland cement with 50% slag in both the mixes. Fly ash was assumed to have no impacts as it is a waste product of electricity generation from coal. Air entraining agent and water retarder impacts were taken from UCPRC LCIs [136]. The LCIA results of PED for the two cases, which include materials and transportation stages, are presented in figure 28, and emissions from concrete and modified concrete production are presented in table 28. The total PED from each constituent of the two concrete mixes is presented in figure 29. The total PED is the same as the consumed PED for the concrete mixes because there are no constituent materials in them made from energy feedstocks.

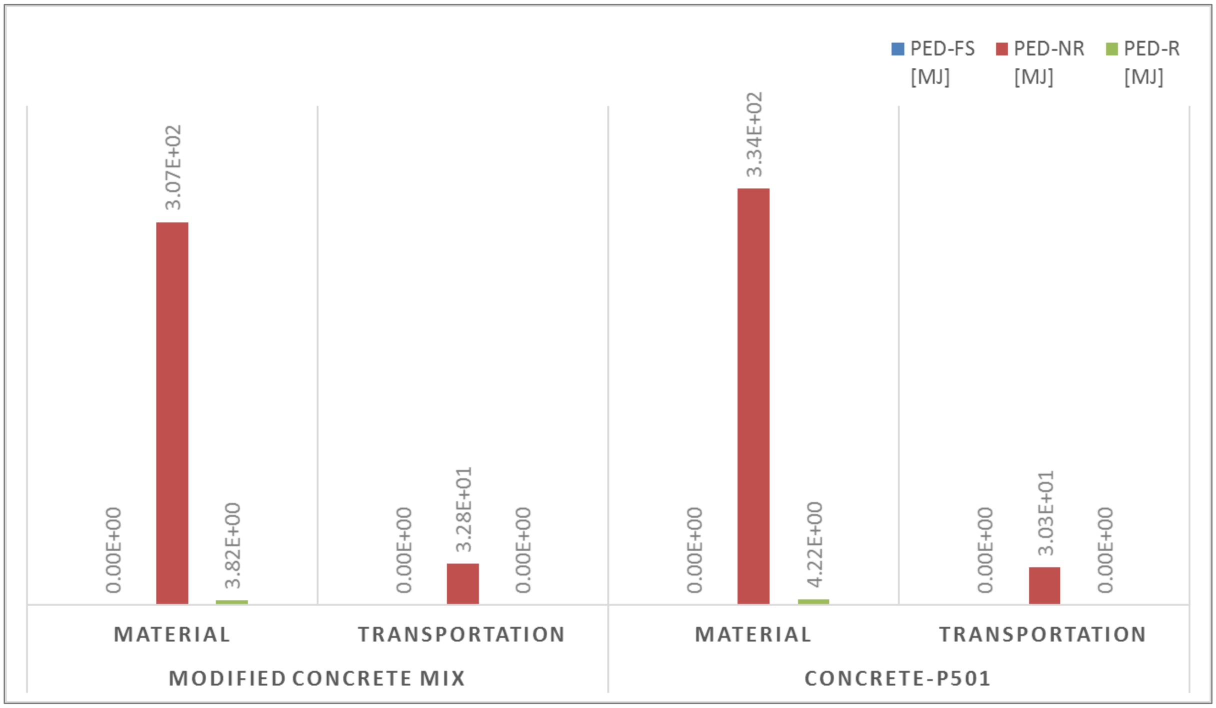


Figure 28. Cradle-to-Gate Analysis of Concrete Mix and Modified Concrete Mix

Table 28. Results for Each Stage per Concrete Material Type

Mix Type	Life Cycle Stage	GWP [kg CO_2-e]	POCP [kg O_3-e]	$PM_{2.5}$ [kg]	PED-NR [MJ]	PED-R [MJ]	PED-FS [MJ]
Modified Concrete Mix	Material	7.44E+01	1.17E+02	5.36E-02	3.07E+02	3.82E+00	0.00E+00
	Transportation	2.29E+00	3.65E-01	7.32E-04	3.28E+01	0.00E+00	0.00E+00
Concrete-P501	Material	7.81E+01	1.16E+02	5.56E-02	3.34E+02	4.22E+00	0.00E+00
	Transportation	2.12E+00	3.37E-01	6.76E-04	3.03E+01	0.00E+00	0.00E+00

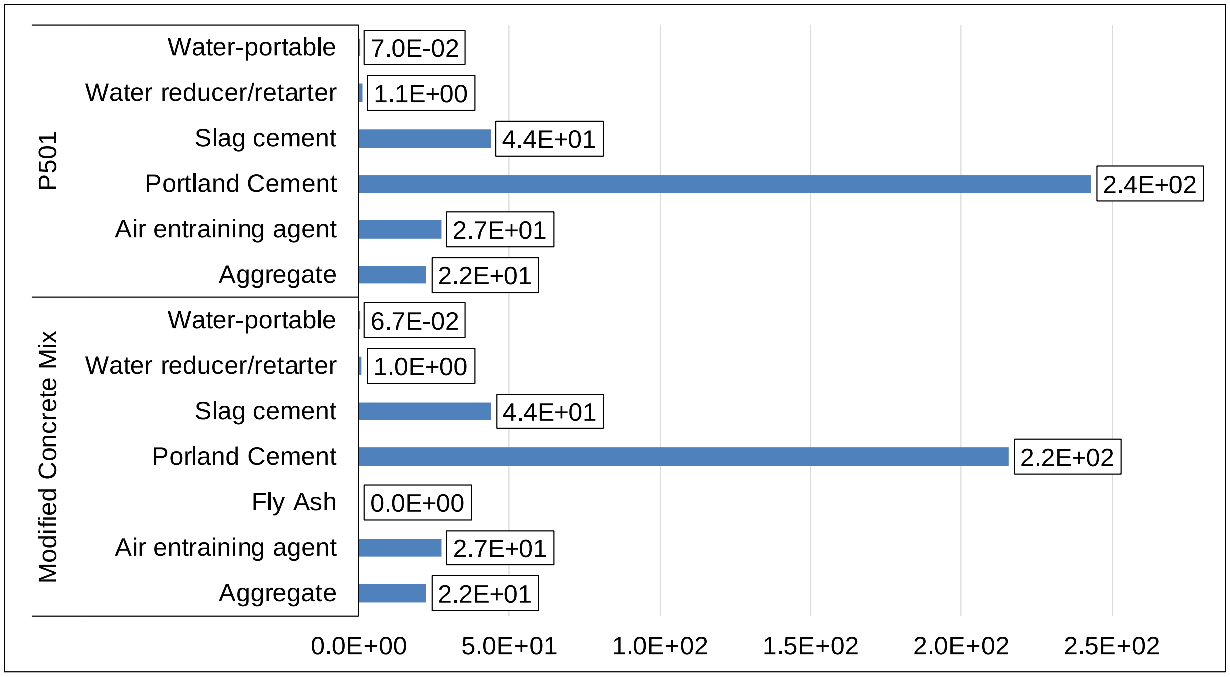


Figure 29. Consumed PED ([PED-NR] + [PED-R] – [PED-FS] in MJ) for Concrete and Modified Concrete Materials

8.4.3 Interpretation.

The results indicate that in terms of resource and environmental impacts, production with WMA with reclaimed materials has lower impacts than production with HMA (that is, consumed nonrenewable PED is about one-third less and emissions are about one-fourth less). This is mainly due to two reasons: less virgin binder being used in WMA and lower mixing temperatures when preparing WMA mixtures. However, production data for the specific GTR, RAS, and Evoflex™ (asphalt additive made of fatty acids) that were used in the WMA were unavailable so production data of crumb rubber, RAP, and fatty acids, respectively, were substituted. Although substituting these materials' inventories introduced some uncertainty into the results, the inventory differences were unlikely to have been large enough to significantly change the interpretation. The transportation of the WMA with reclaimed materials consumed slightly more energy than transportation of the HMA because of the reclaimed materials' additional transport requirements.

These results indicate that use of recyclable materials can potentially reduce energy demand and help in reducing environmental impacts, assuming that the performance is the same. The detailed data in figure 27 show that PED from polymer production (which is used with the HMA) is almost 5.6 times greater than that from recycled rubber production (used with the WMA/GTR), from which it is possible to compare recycled rubber (used in the WMA) versus polymer (used in the HMA). Thus, if GTR does not negatively affect the performance of the asphalt mixtures, it can be used as a polymer additive in some cases and can help in bring down the total PED. If any of these alternatives result in poorer performance than use of standard HMA, then it is possible that the result will be greater environmental impacts. LCA allows the consideration of the changes in environmental impact from these changes in the materials' production and construction, and the effects of the changes on performance to arrive at the life-cycle impacts.

Concrete that uses SCMs and reduced cement content showed lower consumed production energy when compared to the production of conventional P-501 mix (8% less energy). Production of PCC is the most energy-consuming process in the two mixes. The addition of fly ash in the modified concrete mix helped reduce the use of PCC, thus bringing down the total PED. Fly ash, which is an industrial waste, can be used as a binder material with cement in concrete and helps in reduction of environmental impacts. Slag, which is a by-product of iron and steel making, can also be mixed with cement and used in concrete further helping in the reduction of PED and emissions due to cement production. The transportation of materials required for modified concrete mix used slightly more transportation fuel because additional materials required transport.

8.5 BOSTON LOGAN INTERNATIONAL AIRPORT.

8.5.1 Goal and Scope.

BOS is one of the first major airports in the U.S. to incorporate WMA into asphalt concrete specifications for both runway and non-runway sites, and it completed several WMA projects between 2006 and 2015. The goal defined for this case study, in discussions with Massport, was to quantify the environmental impacts of using WMA and RAP in a rehabilitation project and to compare the results against use of conventional HMA. This is an example of a benchmark study. The scope of the study was assumed to be cradle-to-lay, in which the materials production, transportation of the materials to the site, and construction stages are considered. The functional unit was defined as a runway rehabilitation project that was already built.

8.5.2 The LCI and LCIA.

Massport shared documents related to a previously constructed runway rehabilitation project and collected several cores from different sublots. The cross-sectional design thicknesses of the cores, which are summarized in table 29, were extracted from the documents shared by Massport.

Table 30 shows the materials, mix designs, and material producers' information taken from the JMFs of the WMA and conventional HMA P-401 mixes. The WMA mix included a small amount of RAP. The asphalt production plant and quarry locations were extracted from the available information, and the average material transport distances between different facilities were determined using Google Maps™ and are reported in table 31.

In addition to calculating the impacts of the two mixes, sensitivity analyses were also performed to determine the environmental benefits of using WMA versus HMA for the following hypothetical scenarios:

- Reducing the mixing temperature in the case of WMA compared to HMA but keeping the same compaction during construction and assuming same performance.
- Achieving 2% better compaction in the case of WMA and assuming that a 20% longer life is achieved.
- Achieving 4% better compaction in the case of WMA and assuming that a 40% longer life is achieved.

Table 29. Core Cross-Section Thicknesses for Each Sublot per Lot

		Sublot				
Lot Number	Average Thickness (in.)	Core Identification Number	Core Thickness (in.)	Length (ft)	Width (ft)	Quantity of Material (Ton)
1	4	M-1	4.38	142	70	246
1	4	M-2	4	142	70	225
1	4	M-3	3.75	142	70	211
1	4	M-4	3.88	142	70	218
2	4.25	M-5	3.88	142	70	218
2	4.25	M-6	4.38	142	70	246
2	4.25	M-7	4.5	142	70	253
2	4.25	M-8	4.25	142	70	239
3	4.06	M-9	4	202	70	320
3	4.06	M-10	4	202	70	320
3	4.06	M-11	3.88	202	70	310
3	4.06	M-12	4.38	202	70	350
4	4.31	M-13	4.25	113	150	408
4	4.31	M-14	4.5	113	150	432
4	4.31	M-15	4.5	113	150	432
4	4.31	M-16	4	113	150	384
5	4.06	M-17	3.75	97	130	268
5	4.06	M-18	4.25	97	130	304
5	4.06	M-19	3.75	100	130	276
5	4.06	M-20	4.5	100	130	331
6	3.97	M-21	4	1085	10	246
6	3.97	M-22	3.75	1085	10	230
6	3.97	M-23	4.13	1085	10	253
6	3.97	M-24	4	1085	10	246
7	3.86	M-25	3.33	1085	8	164
7	3.86	M-26	3.88	1085	8	190
7	3.86	M-27	4	1085	8	197
7	3.86	M-28	4.25	1085	8	209
8	4.25	M-29	4.5	56	150	214
8	4.25	M-30	4	56	150	190

Table 29. Cores Cross-Section Thicknesses for Each Sublot per Lot (Continued)

		Sublot				
Lot Number	Average Thickness (in.)	Core Identification Number	Core Thickness (in.)	Length (ft)	Width (ft)	Quantity of Material (Ton)
8	4.25	M-31	4.5	56	150	214
8	4.25	M-32	4	56	150	190
9	3.78	M-33	4	55	150	187
9	3.78	M-34	3.38	55	150	158
9	3.78	M-35	3.75	55	150	175
9	3.78	M-36	4	55	150	187
10	3.03	M-37	3.5	188	70	261
10	3.03	M-38	3.25	188	70	242
10	3.03	M-39	2.38	188	70	177
10	3.03	M-40	3	188	70	224

Table 30. The HMA and WMA Mix Designs

Mix Type	Materials	Type/Specifications	Design (% by weight of asphalt mixture)	Comments
P401 (3/4″ WMA)	Asphalt binder	Virgin	4.74	Total asphalt binder = 5.3%
	RAP binder		0.27	5% by weight of asphalt binder
	Latex (SBR)	Styrene butadiene polymer 17%-20%	0.21	4% by weight of asphalt binder
	RAP		15.63	16.5% by weight of aggregate
	Crushed aggregate	Virgin	78.13	Total aggregate = 94.7%
	Lime	High calcium hydrated lime	0.95	1% by weight of aggregate
	Asphalt additive	Sasobit	0.08	1.5% by weight of asphalt binder
P401 (HMA)	Asphalt binder with SBS	PG 76-28	5.32	Total asphalt binder = 5.4%
	Lime	High calcium hydrated lime	0.95	1% by weight of aggregate
	Polymer	SBS	0.08	1.5% by weight of asphalt binder
	Crushed aggregate	Virgin	93.65	Total aggregate = 94.6%

Table 31. Constituent Material Production Facilities and Estimated Transport Distances

Material	Producer	Location		Distance (Miles)
		From	To	
Crushed aggregate	Brox Industries	Dracut, MA	Saugus, MA	30
Crushed aggregate	Aggregate industry	Swampscott, MA	Saugus, MA	5
Asphalt binder with SBS	McCourt Construction Co.	Boston, MA	Saugus, MA	30
Binder	Irving oil terminals	Everett, MA	Saugus, MA	5
HMA	Saugus drum plant	Saugus, MA	Airport, MA	10
Latex (SBR)	Brox Industries	Dracut, MA	Saugus, MA	30
Lime	Madigan	Acton, MA	Airport, MA	35
RAP	Brox Industries	Dracut, MA	Saugus, MA	30
SBS	Brox Industries	Dracut, MA	Saugus, MA	30
WMA	Saugus drum plant	Saugus, MA	Airport, MA	10
Crushed aggregate	Brox Industries	Dracut, MA	Saugus, MA	30
Crushed aggregate	Aggregate industry	Swampscott, MA	Saugus, MA	5
Asphalt binder with SBS	McCourt Construction Co.	Boston, MA	Saugus, MA	30
Binder	Irving oil terminals	Everett, MA	Saugus, MA	5
HMA	Saugus drum plant	Saugus, MA	Airport, MA	10
Latex (SBR)	Brox Industries	Dracut, MA	Saugus, MA	30
Lime	Madigan	Acton, MA	Airport, MA	35
RAP	Brox Industries	Dracut, MA	Saugus, MA	30
SBS	Brox Industries	Dracut, MA	Saugus, MA	30
WMA	Saugus drum plant	Saugus, MA	Airport, MA	10

Table 32 presents the 2015 electricity generation from various sources in Massachusetts [150]. Using the inventory data from table 32, the GaBi database was used to calculate the LCI and LCIA for the production of 1 MJ of electric energy. The total energy consumed (a combination of the primary energy consumed from renewable and nonrenewable resources) and the TRACI results are presented in table 33.

Table 32. Average Electricity Mix of Massachusetts (2015)

Energy Source	Electricity Mix (%)
Coal	6.92
Hydroelectric Conventional	2.54
Natural Gas	64.52
Nuclear	15.34
Other	2.67
Petroleum	2.39
Other Biomass	3.22
Solar Thermal and Photovoltaic	1.39
Wind	0.66
Wood and Wood Derived Fuels	0.37
Total	100

Table 33. Energy Consumption and Environmental Impacts of Electricity Generation in Massachusetts (2015)

Item	Acronym	Unit	Description	Value
Use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials	PED-NR	MJ	Energy from nonrenewable sources that was consumed as fuel and is not available anymore as stored energy in materials	2.66E+00
Use of nonrenewable primary energy resources used as raw materials (feedstock energy)	PED-FS	MJ	Energy from nonrenewable sources that is still available as stored energy in materials	0.00E+00
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PED-R	MJ	Total energy from renewable sources	3.20E-01
Global warming potential, including biogenic carbon, including LUC, no norm/weight	GWP	kg CO_2-e		1.38E-01
Human health: criteria air pollutants	$PM_{2.5}$	Kg	Exposure to elevated $PM_{2.5}$	1.56E-05
Photochemical ozone creation potential	POCP	kg O_3-e	Potential to cause photochemical smog	5.57E-11

Note: Functional unit is 1 MJ of Electricity Delivered on Site

UCPRC material and construction equipment LCIs were used for the case study when case data were unavailable [136]. WMA was produced at 270°F and compacted at 250°F. Sasobit® is paraffin wax–based WMA additive; therefore, LCI data for paraffin wax were used to calculate the LCIA results. Typically, 75 mm lifts are paved and compacted when using HMA; however, 150 mm lifts were used in this project for WMA. The final LCIA results for GWP, POCP, and $PM_{2.5}$, as well as PED, are presented in table 34.

Table 34. Emissions and PED for the Whole Project

Mix Type	Materials	GWP [kg CO_2-e]	POCP [kg O_3-e]	$PM_{2.5}$ [kg]	PED-NR [MJ]	PED-R [MJ]	PED-FS [MJ]
P-401 (3/4″ WMA)	Material	7.91E+05	8.54E+04	4.46E+02	3.36E+07	1.61E+05	2.29E+07
	Construction	6.79E+03	3.00E+03	5.33E+00	9.36E+04	0.00E+00	0.00E+00
	Transportation	2.31E+04	3.68E+03	7.37E+00	3.30E+05	0.00E+00	0.00E+00
	Total	8.20E+05	9.21E+04	4.58E+02	3.40E+07	1.61E+05	2.29E+07
P-401 (HMA)	Material	7.68E+05	7.77E+04	4.05E+02	3.18E+07	1.54E+05	2.16E+07
	Construction	3.40E+03	1.50E+03	2.67E+00	4.68E+04	0.00E+00	0.00E+00
	Transportation	4.96E+04	7.91E+03	1.59E+01	7.10E+05	0.00E+00	0.00E+00
	Total	8.21E+05	8.71E+04	4.24E+02	3.26E+07	1.54E+05	2.16E+07

8.5.3 Interpretation.

The baseline results for the WMA mix used are shown in table 34. These results could be compared to other alternatives or projects that are currently being executed or have been completed to see how they differ. A sensitivity analysis was performed to compare this WMA project with a conventional HMA project.

8.5.4 Sensitivity Analysis.

For the sensitivity analysis, it was assumed that the quantity of HMA mix used for the rehabilitation of the runway would be the same as the quantity of WMA mix used. Documents provided by Massport for a typical P-401 HMA mix design were used to evaluate the HMA alternative (table 30). As shown in figure 30, WMA has an approximately 4% lower PED than the HMA, mainly due to differences in virgin asphalt binder content as well as to the lower mix temperature for WMA. Although they make a very small contribution to the total, the impacts for HMA construction are double those of WMA as HMA is constructed in 75 mm lifts and WMA was placed in 150 mm lifts. The emissions for HMA production were also higher for a conventional HMA as compared to the WMA as shown in figure 30. Impacts from transportation were not that high as the material transportation was on short distances.

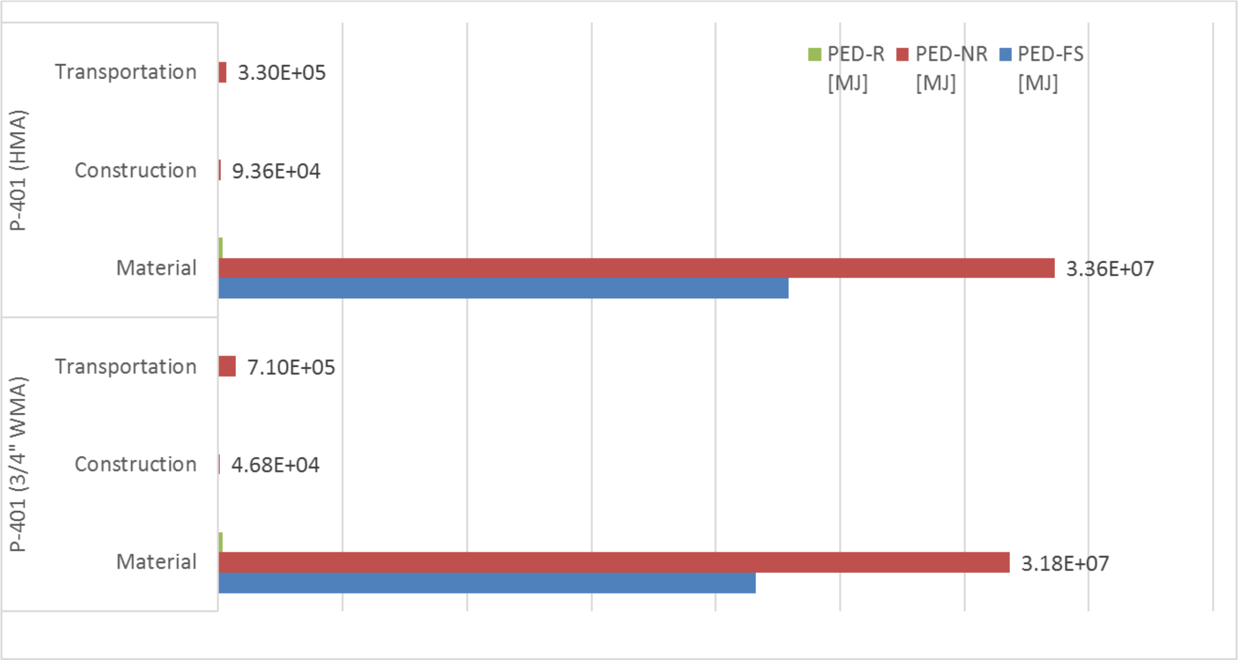


Figure 30. The PED Comparison Between HMA and WMA

Figure 31. The GWP (kg of CO_2-e) Comparison Between HMA and WMA

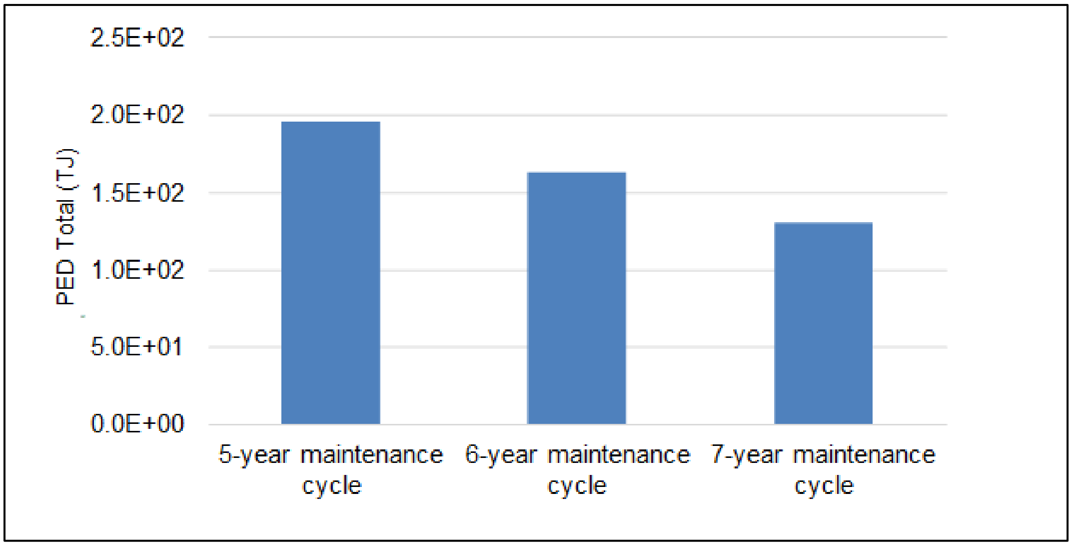
Two hypothetical cases were considered: one assumed a 30-year pavement design life and the other assumed a baseline 5-year maintenance cycle for replacement of the surface layer (referred to as mill and fill) using WMA. Three scenarios were considered:

1. Scenario 1 assumed a 5-year maintenance cycle.

2. Scenario 2 assumed 2% better compaction, which increases the assumed maintenance cycle by 20% to 6 years.

3. Scenario 3 assumed 2% better compaction, which increases the assumed maintenance cycle by 40% to 7 years.

The 30-year total PED (from renewable and nonrenewable resources) is shown in figure 32 and selected TRACI emissions in tonnes for the project are shown in figure 33 for the three scenarios. A comparison of scenarios 1 and 2 shows that almost all the PED and environmental impacts can be reduced by approximately 17% if the hypothetical improvement of 2% better compaction results in increasing the maintenance cycle from 5 to 6 years over the 30-year analysis period. These reductions are doubled to approximately 33% if the hypothetical improvement of 4% better compaction is achieved with WMA, resulting in an increase in the maintenance cycle from 5 to 7 years.



Note: TJ = terajoules

Figure 32. Total PED ([PED-NR] + [PED-R]) for Three Different Scenarios

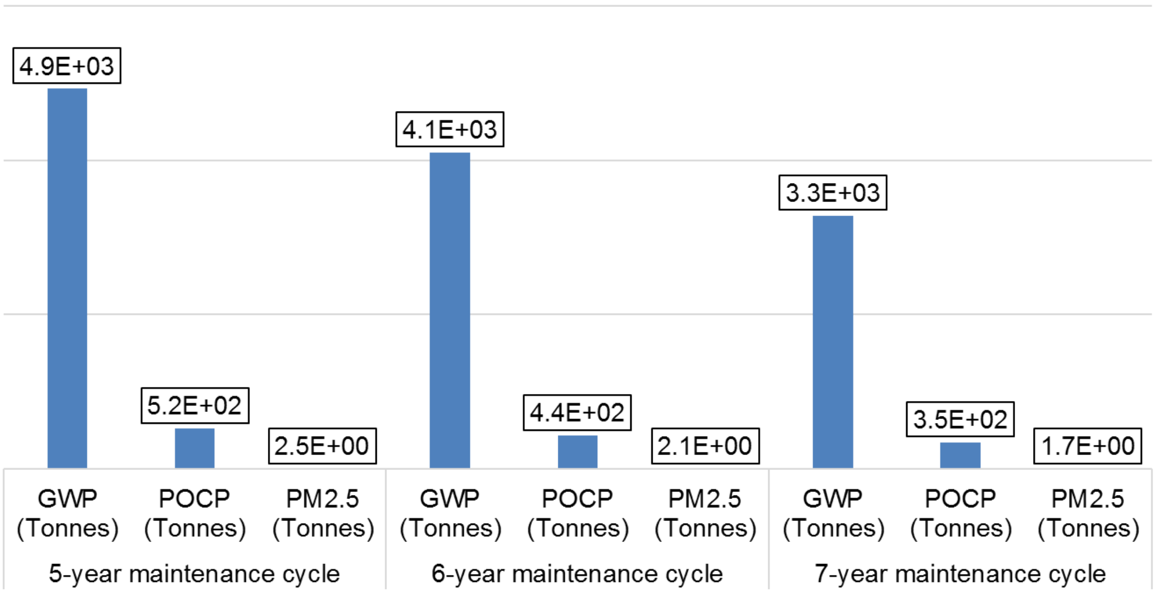


Figure 33. Selected TRACI Impacts (in tonnes) for Three Different Scenarios

8.6 NASHVILLE INTERNATIONAL AIRPORT.

8.6.1 Goal and Scope.

Information for this case study was gathered from a reconstruction project on Taxiway Sierra, which was completed in 2016. Several asphalt and concrete pavement design alternatives were proposed and, based on the least LCCA, one concrete cross section and one asphalt pavement cross section were selected for the project. The UCPRC and Atkins, BNA's consultant on the project, decided that the goal of the study would be to use LCA to evaluate the environmental impacts of all the design alternatives within each type—that is, asphalt sections would be compared with other asphalt sections, and concrete sections would be compared with other concrete sections.

This is an example of a comparative LCA study. Comparative studies can be used to compare different pavement design alternatives, and the results can be used with LCCA to help airports make much more informed decisions regarding both sustainability and cost. It is very important to note that comparisons must consider the complete life cycles of the alternatives being compared, not just one part of the life cycle, such as initial construction or the use stage. For this case study, each of the alternative pavement cross sections within each pavement type (asphalt and concrete) was assumed to have the same maintenance cycle, time to next rehabilitation, use stage, and EOL scenario. This means that the materials, construction, and transportation stages were the only parts of the life cycle that differed. The concrete and asphalt cross sections cannot be compared to each other because they will likely have different results for these parts of the life cycle.

The scope of the study was from cradle-to-lay, in which the materials and construction stages of the life cycle of the pavements and the transportation of materials are considered. The functional unit defined for the case study was the construction of a taxiway sublot where the sublot length was set as 100 ft and the width as 50 ft. A functional unit of this type can be scaled for pavements that have varying widths or thicknesses, and could also be used for airside vehicle roads, shoulders, drainages, and aprons.

8.6.2 The LCI and LCIA.

With the permission of BNA, Atkins shared several documents with UCPRC related to the taxiway reconstruction project. Pavement cross-section designs for the different proposed asphalt and concrete alternatives (figures 34 and 35) were extracted from the Taxiway Sierra reconstruction project drawings and the engineer's final report. Figure 34 shows the alternative using typical standard cross sections; which are labeled with an R. Figure 35 shows the alternative using nonstandard cross sections that are based on standard engineering practices but which are not commonly used; they are referred to here as "nonstandard designs" and are labeled with NS in the figure. A total of seven design alternatives were proposed, five of which were standard designs and two were nonstandard designs. Four of the alternatives were concrete pavements and three were asphalt pavements. The cross-section information is also shown in table 35.

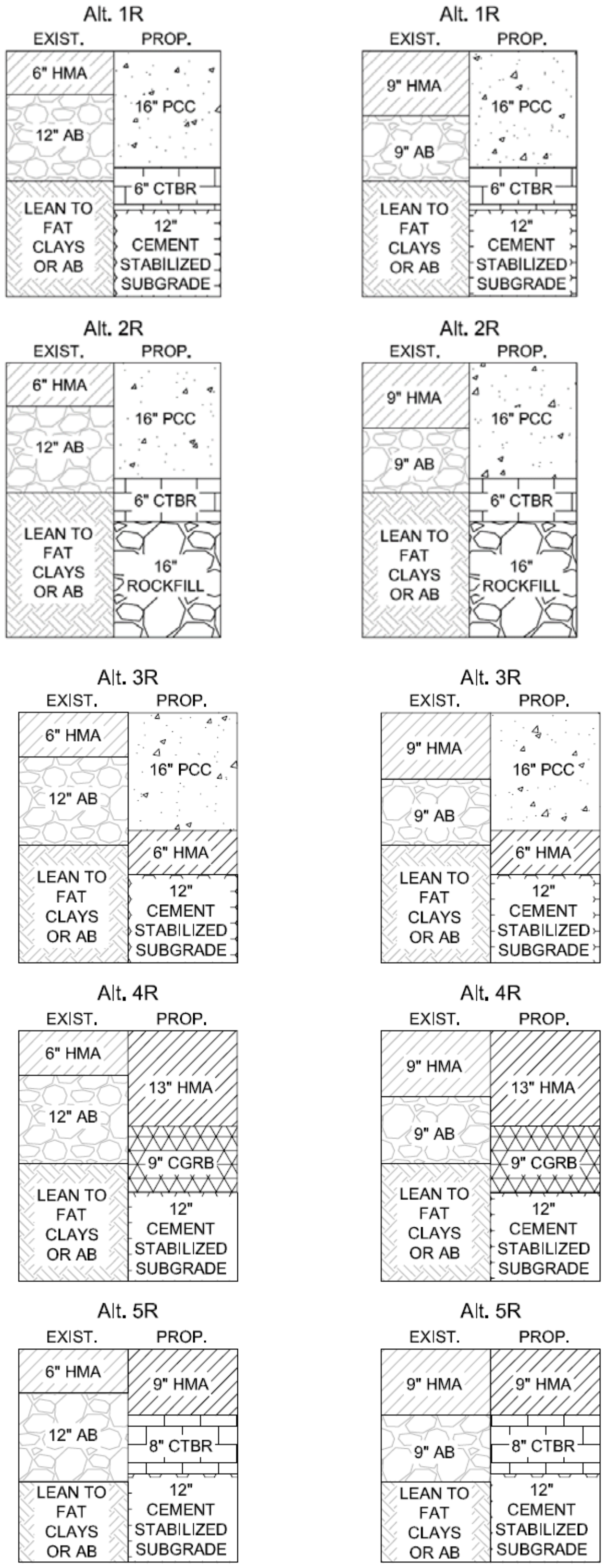


Figure 34. Alternative Standard Cross Sections for the Asphalt and Concrete Pavements

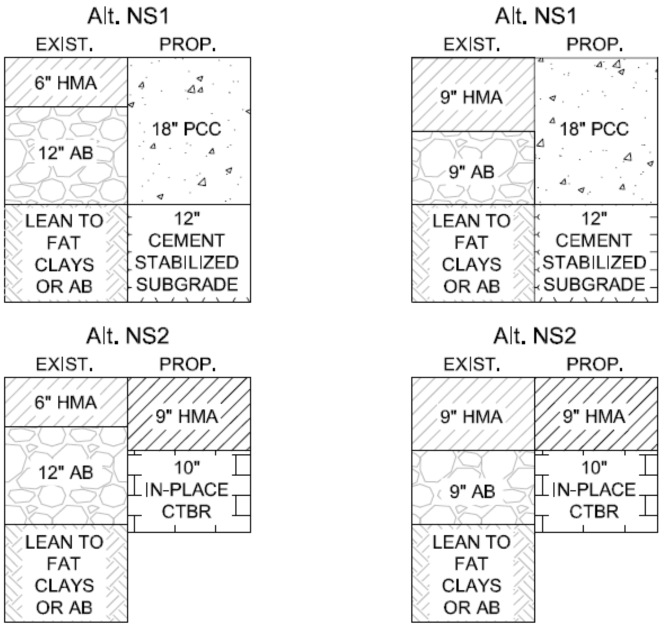


Figure 35. Alternative Nonstandard Cross Sections for the Asphalt and Concrete Pavements

Table 35. Cross-Section Pavement Thickness Design Alternatives for Asphalt and Concrete Pavements

Atkins Selected Based on LCCA	Pavement Thickness Design Alternates	Layer 1 Type	Layer 1 Thick. (in.)	Layer 2 Type	Layer 2 Thick. (in.)	Layer 3 Type	Layer 3 Thick. (in.)	Mix Design Layer 1	Mix Design Layer 2	Mix Design Layer 3
X	1R	PCC	16	CTBR	6	CSS	12	P501	P304-P207	P155
	2R	PCC	16	CTBR	6	Rf	16	P501	P304-P207	P152
	3R	PCC	16	HMA	6	CSS	12	P501	P403	P155
	NS1	PCC	18	CSS	12	-	-	P501	P301	-
	4R	HMA	13	CGRB	9	CSS	12	P401	P209	P155
	5R	HMA	9	CTBR	8	CSS	12	P401	P304-P207	P155
X	NS2	HMA	9	iCTBR	10	-	-	P401	P304-P207	-

Notes:
CGRB = Crushed graded reclaimed base
CSS = Cement-stabilized subgrade
CTBR = Cement-treated base with reclaimed aggregate
iCTBR = In-place cement-treated base with reclaimed aggregate
Rf = Rockfill

Mix designs for the different materials used in the pavement design alternatives were extracted from the JMF documents and engineer's final report and are summarized in table 36. The construction information, such as the lift thicknesses, were extracted from the specification documents. Table 37 includes the material producers' information, material production plant, and quarry locations were also collected from the documents, and the average material transport distances between the different facilities determined using Google Maps™.

Table 36. Mix Design for Different Materials Proposed for Construction Use

Mix Type	Materials	Type	Mix Design (%)
P-401 (HMA 3/4″ surface)	Asphalt binder	PG 76-22	5
	Crushed aggregate	#7 soft limestone	38
		#10 soft limestone	14.25
		#10 washed-soft limestone	28.5
		natural sand	14.25
P-401 (HMA 1″ base course) equals P403	Asphalt binder	PG 64-22	3.6
	Crushed aggregate	#67 soft limestone	23.9
		#7 soft limestone	23.9
		#10 soft limestone	14.3
		natural sand	14.3
	RAP	processed -3/4	20.0
P-301 (CSS)-nonstandard	PCC	-	6
P-155 (CSS)-standard	PCC	-	4
P-304 (CTB)	PCC	-	5
P-304 (iCTB)	PCC	-	6

Table 37. Different Material Production Facilities and Estimated Transport Distances

Design Alt.	Mix Type	Material	Producer	Location		Distance (Miles)
				From	To	
1R	PCC	Cement		Assume same as asphalt	Concrete mix plant	10
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville concrete plant	30
		Air entraining agent		Assume same as cement	Concrete mix plant	5
		Water	Jones Bros. Contractors	Nashville, TN	Jones Bros. Contractors; Nashville concrete plant	10
		Concrete	Jones Bros. Contractors	Plant	Nashville airport	5
	CTBR	Cement		Assume same as asphalt	Concrete mix plant	5
		CTBR	Jones Bros. Contractors	Plant	Nashville airport	5
	CSS	Cement		Plant	Airport	5
2R	PCC	Cement		Assume same as asphalt	Concrete mix plant	5
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		Air entraining agent		Assume same as cement	Concrete mix plant	5
		Concrete	Jones Bros. Contractors	Plant	Nashville airport	5
	CTBR	Cement		Assume same as asphalt	Concrete mix plant	5
		CTBR	Jones Bros. Contractors	Plant	Nashville airport	5

Table 37. Different Material Production Facilities and Estimated Transport Distances (Continued)

Design Alt.	Mix Type	Material	Producer	Location		Distance (Miles)
3R	PCC	Cement		Assume same as asphalt	Concrete mix plant	5
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		Air entraining agent		Assume same as cement	Concrete mix plant	5
		Concrete	Jones Bros. Contractors	Plant	Nashville airport	5
	HMA	Asphalt binder	Ergo Asphalt Emulsions, Nashville terminal (1114 Visco Drive, Nashville)	Nashville, TN	Jones Bros. Contractors	10
		RAP binder	Ergon Asphalt Emulsions, Nashville terminal (1114 Visco Drive, Nashville)	Nashville, TN	Jones Bros. Contractors	10
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		HMA		Nashville Asphalt Mix	Nashville, TN	5
	CSS	Cement		Plant	Airport	5
NS1	PCC	Cement				5
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		Air entraining agent		Assume same as cement	Concrete mix plant	5
		Water				
		Concrete	Jones Bros. Contractors	Plant	Nashville airport	5
	CSS	Cement		Plant	Airport	5
4R	HMA	PG 76-22	Ergon Asphalt Emulsions, Nashville terminal (1114 Visco Drive, Nashville)	Nashville, TN	Jones Bros. Contractors; Nashville Asphalt Mix	10
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		HMA		Nashville Asphalt Mix	Nashville, TN	5
	CCRB	RAB		Nashville Asphalt Mix	Nashville, TN	5
	CSS	Cement		Plant	Airport	5

Table 37. Different Material Production Facilities and Estimated Transport Distances (Continued)

Design Alt.	Mix Type	Material	Producer	Location		Dist. (Miles)
5R	HMA	PG 76-22	Ergon Asphalt Emulsions, Nashville terminal (1114 Visco Drive, Nashville)	Nashville, TN	Jones Bros. Contractors; Nashville Asphalt Mix	10
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		HMA		Nashville Asphalt Mix	Nashville, TN	5
	CTBR	Cement		Assume same as asphalt	Concrete mix plant	5
		RAB		Nashville Asphalt Mix	Nashville, TN	5
	CSS	Cement		Plant	Airport	5
NS2	HMA	PG 76-22	Ergon Asphalt & Emulsions, Nashville terminal (1114 Visco Drive, Nashville)	Nashville, TN	Jones Bros. Contractors; Nashville Asphalt Mix	10
		Crushed aggregate	Vulcan Materials, Nashville Danley plant	Nashville, TN	Nashville Asphalt Mix	30
		HMA		Nashville Asphalt Mix	Nashville, TN	5
	iCTBR	Cement		Plant	Airport	5

Table 38 presents the 2015 electricity mix for Tennessee [150] that was used for this case study to calculate the impacts for different materials and processes. Using the inventory data from table 38, the GaBi database was used to calculate the LCI and LCIA to produce 1 MJ of electric energy. The total energy consumed (combination of the primary energy from renewable and nonrenewable resources) and selected TRACI impact indicator results are presented in table 39.

Table 38. Average Electricity Mix of Tennessee (2015)

Energy Source	Electricity Mix (%)
Coal	40.38
Hydroelectric Conventional	12.65
Natural Gas	12.31
Nuclear	32.95
Other Gases	0.02
Other	0.03
Petroleum	0.18
Solar Thermal and Photovoltaic	0.10
Other Biomass	0.11
Wind	0.06
Wood and Wood Derived Fuels	1.22
Total	100

Table 39. Energy Consumption and Environmental Impacts of Electricity Generation in Tennessee (2015)

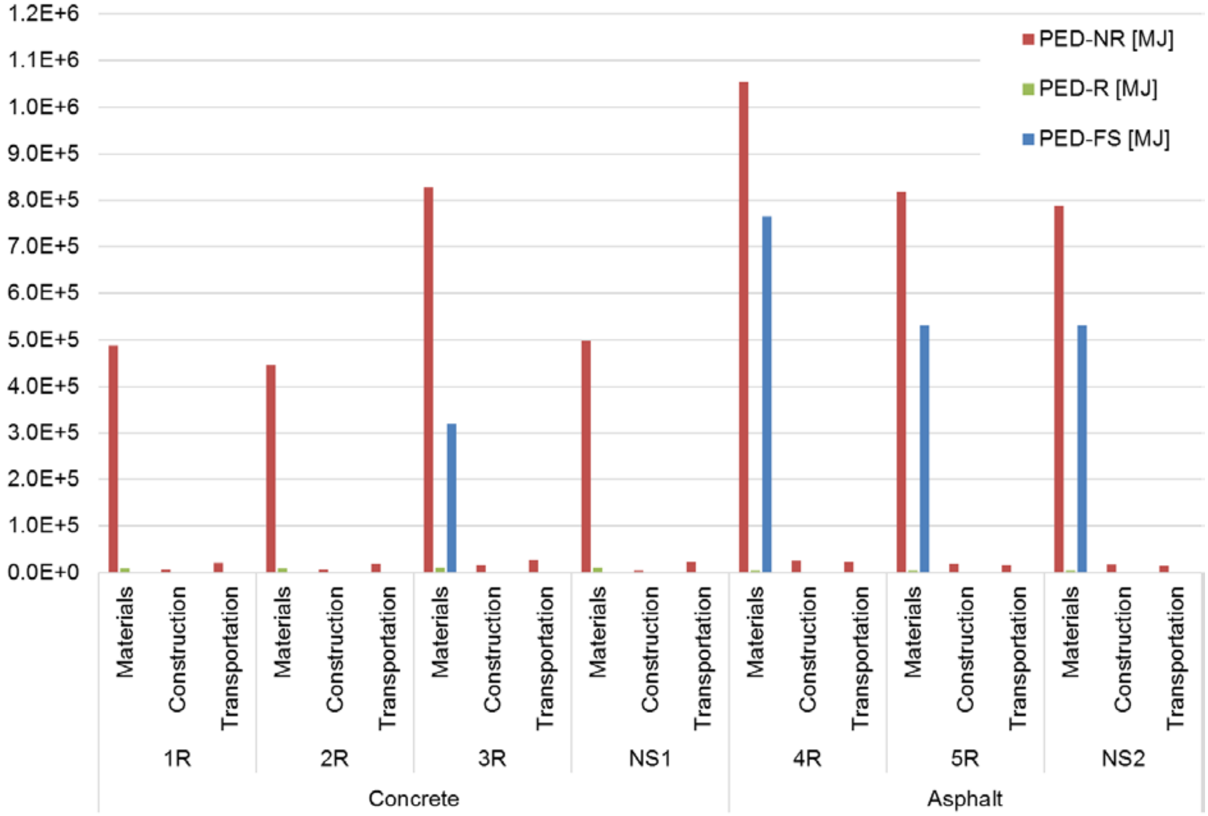
Item	Acronym	Unit	Description	Value
Use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials	PED-NR	MJ	Energy from nonrenewable sources that was consumed as fuel and is not available anymore as stored energy in materials	2.65E+00
Use of nonrenewable primary energy resources used as raw materials (feedstock energy)	PED-FS	MJ	Energy from nonrenewable sources that is still available as stored energy in materials	0.00E+00
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PED-R	MJ	Total energy from renewable sources	2.30E-01
Global warming potential, including biogenic carbon, including LUC, no norm/weight	GWP	kg CO_2-e		1.45E-01
Human health: criteria air pollutants	$PM_{2.5}$	Kg	Exposure to elevated particulate matter less than 2.5 micrometer	2.22E-05
Photochemical ozone creation potential	POCP	kg O_3-e	Potential to cause photochemical smog	1.19E-10

Note: Functional unit is 1 MJ of electricity delivered on site.

UCPRC material and construction equipment LCIs were used for the case study where data were unavailable [136]. The cut-off method was used for allocation of impacts between upstream projects where virgin materials were initially used and the current project where recycled/reclaimed materials are consumed. Only the impacts of construction activities to pulverize the old surface and obtain reclaimed materials plus transportation to the site were assigned to RAP. The flow and impact data for operation of the machinery used in the mixing process for in-plant cement-treated base with CTBR, in-place CTBR, and CSS were not available, and therefore, their impacts were not considered in the materials stage. The case study results are presented in table 40 and figures 36 and 37.

Table 40. The PED and Selected TRACI Emissions in Each Stage per Pavement Design Alternative

Type	Design Alternative	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3-e]	$PM_{2.5}$ [kg]	PED-NR [MJ]	PED-R [MJ]	PED-FS [MJ]	PED-Fuel [MJ]	PED-Total [MJ]
Concrete	1R	Materials	7.0E+4	5.5E+2	6.0E+3	4.9E+5	1.0E+4	0.0E+0	5.0E+5	5.0E+5
		Construction	3.8E+2	1.7E+2	3.0E-1	5.3E+3	0.0E+0	0.0E+0	0.0E+0	5.3E+3
		Transportation	1.5E+3	2.3E+2	4.7E-1	2.1E+4	0.0E+0	0.0E+0	2.1E+4	2.1E+4
		TOTAL	7.2E+4	9.5E+2	6.0E+3	5.1E+5	1.0E+4	0.0E+0	5.2E+5	5.2E+5
	2R	Materials	6.2E+4	5.5E+2	5.4E+3	4.5E+5	1.0E+4	0.0E+0	4.6E+5	4.6E+5
		Construction	3.8E+2	1.7E+2	3.0E-1	5.3E+3	0.0E+0	0.0E+0	0.0E+0	5.3E+3
		Transportation	1.4E+3	2.2E+2	4.4E-1	2.0E+4	0.0E+0	0.0E+0	2.0E+4	2.0E+4
		TOTAL	6.3E+4	9.4E+2	5.4E+3	4.7E+5	1.0E+4	0.0E+0	4.8E+5	4.8E+5
	3R	Materials	6.6E+4	3.9E+2	6.1E+3	8.3E+5	1.1E+4	3.2E+5	5.2E+5	8.4E+5
		Construction	1.2E+3	5.2E+2	9.3E-1	1.6E+4	0.0E+0	0.0E+0	0.0E+0	1.6E+4
		Transportation	1.9E+3	3.0E+2	6.1E-1	2.7E+4	0.0E+0	0.0E+0	2.7E+4	2.7E+4
		TOTAL	6.9E+4	1.2E+3	6.1E+3	8.7E+5	1.1E+4	3.2E+5	5.5E+5	8.8E+5
	NS1	Materials	7.3E+4	3.8E+2	6.4E+3	5.0E+5	1.1E+4	0.0E+0	5.1E+5	5.1E+5
		Construction	3.3E+2	1.5E+2	2.6E-1	4.6E+3	0.0E+0	0.0E+0	0.0E+0	4.6E+3
		Transportation	1.6E+3	2.5E+2	5.0E-1	2.2E+4	0.0E+0	0.0E+0	2.2E+4	2.2E+4
		TOTAL	7.4E+4	7.8E+2	6.4E+3	5.3E+5	1.1E+4	0.0E+0	5.3E+5	5.4E+5
Asphalt	4R	Materials	2.2E+4	3.5E+2	2.6E+3	1.1E+6	4.5E+3	7.7E+5	2.9E+5	1.1E+6
		Construction	1.9E+3	8.4E+2	1.5E+0	2.6E+4	0.0E+0	0.0E+0	0.0E+0	2.6E+4
		Transportation	1.5E+3	2.5E+2	4.9E-1	2.2E+4	0.0E+0	0.0E+0	2.2E+4	2.2E+4
		TOTAL	2.5E+4	1.4E+3	2.6E+3	1.1E+6	4.5E+3	7.7E+5	3.2E+5	1.1E+6
	5R	Materials	2.8E+4	3.0E+2	2.9E+3	8.2E+5	4.9E+3	5.3E+5	2.9E+5	8.2E+5
		Construction	1.4E+3	6.3E+2	1.1E+0	2.0E+4	0.0E+0	0.0E+0	0.0E+0	2.0E+4
		Transportation	1.1E+3	1.8E+2	3.5E-1	1.6E+4	0.0E+0	0.0E+0	1.6E+4	1.6E+4
		TOTAL	3.1E+4	1.1E+3	2.9E+3	8.5E+5	4.9E+3	5.3E+5	3.1E+5	8.6E+5
	NS2	Materials	2.3E+4	3.6E+2	2.5E+3	7.9E+5	4.2E+3	5.3E+5	2.6E+5	7.9E+5
		Construction	1.3E+3	5.9E+2	1.0E+0	1.8E+4	0.0E+0	0.0E+0	0.0E+0	1.8E+4
		Transportation	9.7E+2	1.5E+2	3.1E-1	1.4E+4	0.0E+0	0.0E+0	1.4E+4	1.4E+4
		TOTAL	2.6E+4	1.1E+3	2.5E+3	8.2E+5	4.2E+3	5.3E+5	2.8E+5	8.3E+5



Note: PED-FS is feedstock energy in materials made from petroleum; this energy was not consumed.

Figure 36. The PED (PED-NR and PED-R) and PED-FS in Each Life-Cycle Stage for Each Pavement Design Alternative

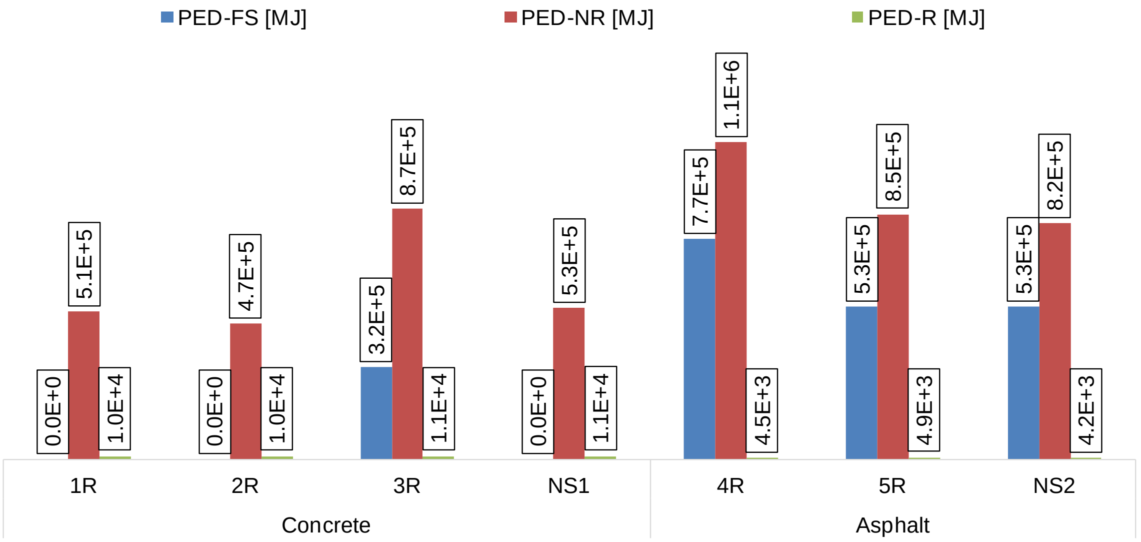


Figure 37. The PED per Pavement Design Alternative

8.6.3 Interpretation.

8.6.3.1 Concrete Alternatives.

A comparison of the four concrete alternatives (1R, 2R, 3R, and NS1) showed that NS1 had the highest GHG and PM2.5 emissions, while 3R had the highest smog formation and total PED. However, it should be noted that 3R is the only one of the four concrete options that has feedstock energy, which is due to that concrete pavement's second layer being made of HMA. Of the four concrete options, Alternative 2R had the least impact across all categories except for smog formation. The total PED of design alternative 3R was 84% more than alternative 2R. The materials production stage was the dominant life cycle stage across all alternatives, accounting for more than 96% of total GHG emissions.

Decision support in selection of the design alternative based on 30-year LCCA suggests 1R to be the most cost-effective alternative; however if environmental considerations are prioritized, then alternative 2R is preferable.

8.6.3.2 Asphalt Alternatives.

Of the three asphalt alternatives (4R, 5R, and NS2), 5R had the highest environmental impacts for the TRACI indicators (GWP and $PM_{2.5}$), while 4R had the highest consumed PED-FS (feedstock energy). NS2 had the lowest impact in terms of energy required and emissions, although not for GWP (due to the high cement content of this alternative). The total PED determined for NS2 was 4% lower than 5R and 25% lower than 4R. As with the concrete alternatives, transportation and construction were not major contributors to any impact category other than smog formation; and in this category construction was consistently the dominant contributor, with 53% to 59% of total smog formation across all alternatives. It is important to note that equipment operation impacts for the cement-treated bases were not included, as they were in the cases for concrete.

In a 30-year LCCA, it was determined that NS2 was the most economical option. LCA (cradle-to-lay) results also determined that NS2 was the most environmentally feasible option.

This case study shows that performing LCCA and LCA together provides opportunity for the airports to consider not only costs but also energy and a number of environment-related impacts for decision support in the selection of more sustainable pavement design alternatives.

9. SUMMARY AND RECOMMENDED FUTURE WORK.

9.1 SUMMARY.

For the project documented in this report, the research team, working with the FAA project team, other experts, and the staff or consultants from four airports, used existing life-cycle assessment (LCA) knowledge, practice, and studies to comprehend the scope and life cycles of airfield pavements and best practices for environmental LCA. The result of this work is the LCA framework for airfield pavement presented in this report. The framework is intended to provide preliminary definitions for the basic elements of airfield pavement LCA and to provide recommendations for the conduct of airfield airside LCA studies for features other than buildings.

Section 8 of this report includes four case studies performed using the LCA framework and available data. These initial case studies demonstrate the capability of the LCA framework for quantifying the life-cycle environmental impacts of airfields so that airports can better understand environmental impacts and improve airfield system sustainability. The goals and scoping data for the case studies were developed from discussions with staff and/or consultants from the four airfields. These initial case studies all focused on questions related to the materials, construction, and transportation stages of the life cycle, although one study also considered changes in maintenance overlay frequency.

9.2 RECOMMENDED FUTURE WORK.

The following five tasks are recommended as the next steps in further developing airports' ability to consider life-cycle environmental impacts in their decision-making.

1. Submit the LCA framework to outside review and critique.

   To complete this task, the proposed plan should be submitted to a panel of experts with domain expertise in the areas of LCA, airfield engineering and management, and preferably both. This task would follow established recommended practice for LCA. The results would be written recommendations for any changes to the framework based on their review, followed by an updated version of the framework, until the panel of experts are satisfied that their critiques were adequately addressed.

   The deliverable would be a revised LCA framework, approved by the critical review panel, with documentation of the critical review results.

2. Develop and deliver initial training to the FAA.

   The purpose of this task is to build a better understanding of environmental impacts and to examine potential strategies that airport staff and consultants can consider to improve airfield system sustainability. The deliverables would be training materials summarizing the framework for performing airfield LCA studies, an LCA framework demonstration through the initial case studies in this report, and selected additional case studies demonstrating a broad range of applications.

3. Develop a plan for establishing complete analysis capability for airports using the developed framework.

   This task requires review of the LCA framework, after completion of task 1, and review of resources that airports have available for performing LCA studies based on the initial case studies. This should be followed by development of a plan for fully establishing an LCA capability for the FAA, which will include these items at least:

   - Identification of data that airports would need to supply and data that would need to be supplied to them

   - Models for all processes to be considered by the FAA on a routine basis

- Data sources, including:
    - Data collected by FAA
    - Access to data from commercial sources
    - Data obtained from other sources
- Software and other tools
- Training
- Processes for consideration of LCA in decision-making

The deliverable would be a detailed plan for establishing a complete analysis capability for airports.

4. Develop a first-version LCA tool for airports.

This task would execute the plan from task 2, and includes development of the database, building on existing databases and modeling processes for highways but adapting or adding to them where there are differences between highways and airfields, or scope that exists on airfields but not on highways. These will be used in the tool to analyze the required environmental inputs and outputs, and reflect regional or airfield-specific technology and practices. The next step would be using the database and modeling processes to develop a modeling tool and software to assist decision-making for airfield pavements. The deliverable would be the software tool.

5. Outreach and training with the LCA framework.

The final task would be to develop and deliver outreach and training activities regarding LCA, and the framework and tool, developed to help FAA and airfield staff. Support would also be provided for use of the tool and support to airports in performing their own initial case studies. The purpose is to provide a better understanding of environmental impacts and potential sustainability improvement strategies for the airfield system in each phase over the entire life cycle (including materials, construction, use phase, maintenance and rehabilitation, and end-of-life). The deliverables would be the training materials summarizing the procedure and resources for performing airfield LCA studies and demonstrating the LCA framework and tool for the FAA and airfields.

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