NRC·CNRC

NRC Publications Archive
Archives des publications du CNRC

National guidelines for Canadian highway bridge life cycle assessment

Achebe, Jessica; Zhang, Jieying; Rana, Anber; Hojjati, Aryan; Amor, Ben

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

https://doi.org/10.4224/40004078

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=d5692003-8cd4-4627-8161-b384991152f2
https://publications-cnrc.canada.ca/fra/voir/objet/?id=d5692003-8cd4-4627-8161-b384991152f2

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada | Conseil national de recherches Canada

Canada

NRC·CNRC

National Guidelines for Canadian Highway Bridge Life Cycle Assessment

NRC·CNRC



National Research Council Canada
Conseil national de recherches Canada

Canada

National Guidelines for Canadian Highway Bridge Life Cycle Assessment

Authors

Jessica Achebe, Ph.D., P.Eng., Co-Principal Investigator

Jieying Zhang, Ph.D., P.Eng., Project Manager and Co-Principal Investigator

Anber Rana, Ph.D.

Aryan Hojjati, Ph.D.

Ben Amor, Ph.D., P.Eng.

National Research Council Canada

Acknowledgment

These guidelines for life cycle assessment (LCA) of Canadian highway bridges were produced by the Centre of Excellence for Construction Life Cycle Assessment (CECLCA) of the National Research Council Canada (NRC), under the leadership of Dr. Jieying Zhang, as part of the Low Carbon Built Environment (LCBE) challenge program.

We gratefully acknowledge the support of the technical committee members, who contributed their expertise as bridge asset managers, decision-makers, designers, and LCA specialists and provided valuable feedback during the development and review of these guidelines. Special thanks are extended to Mr. Craig McLeod of the Ministry of Transportation of Ontario (MTO) for his insightful comments and for supplying bridge data for LCA case studies, and to Ms. Laura Husak of Housing, Infrastructure and Communities Canada (HICC) for her thoughtful discussions.

Disclaimer

This guidelines document may not be reproduced in whole or in part without the written consent of the National Research Council Canada. It is intended for use by qualified practitioners and researchers and to inform bridge communities about facilitating low-carbon and sustainable design and management of highway bridges in Canada. The NRC cannot be held liable for any damages or claims resulting from using or misusing the guidelines.

Recommended Citation:

Achebe, J., Zhang, J., Rana, A., Hojjati, A., and Amor, B. (2026). National Guidelines for Canadian Highway Bridge Life Cycle Assessment. National Research Council Canada.

Copyright

©His Majesty the King in Right of Canada, as represented by the National Research Council Canada**.**

Technical Reviewers

Members	Affiliation
Craig McLeod	Ministry of Transportation of Ontario (MTO)
Hessam Azarijafari	Massachusetts Institute of Technology (MIT)
Jianping Jiang	WSP
Joep Meijer	The Right Environment
John T. Harvey	University of California, Davis
Kris Mermigas	Ministry of Transportation of Ontario (MTO)
Laura Husak	Housing, Infrastructure and Communities Canada
Marc-Alexandre Allard	Ministère des Transports du Québec (MTQ)
Marie-Hélène Tremblay	Ministère des Transports du Québec (MTQ)
Mick Prieur	Cement Association of Canada
Peter Bacas	ERG (Eastern Research Group)
Tim Smith	Cement Association of Canada, Retired

Abstract

This document provides a national framework and practical guidance for conducting Life Cycle Assessment (LCA) of Canadian highway bridges. The purpose is to establish a harmonized and consistent methodology for quantifying the environmental impacts of bridges across their entire life cycle—from design and construction through maintenance, repair, and end-of-life phases—with particular emphasis on greenhouse gas (GHG) emissions. This Guideline is a foundational step toward integrating environmental performance into bridge planning and design, promoting more sustainable infrastructure across Canada.

The Guideline serves following key objectives:

- Standardize the practice of Bridge LCA across Canada to improve comparability, transparency, and quality of assessment.
- Support integration of LCA into bridge design practices, including future incorporation into the Canadian Highway Bridge Design Code (CSA S6).
- Enable alignment among Bridge LCA tools and datasets through a common framework and terminology.
- Facilitate using LCA in infrastructure policy, funding eligibility, and environmental compliance programs to support Canada's climate and sustainability goals.

This document is intended for users across the bridge construction value chain, including policymakers, infrastructure planners, bridge owners and operators, design engineers, material suppliers, LCA practitioners, and tool developers.

The methodology presented aligns with international standards (ISO 14040:2006 and ISO 14044:2006) and adheres to the four classical phases of LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation.

The document is structured as follows:

- Chapter 1 outlines the background and rationale for conducting Bridge LCA in the Canadian context.
- Chapter 2 provides an overview of various bridge systems, the life cycle of a bridge, and stakeholder engagement in LCA.
- Chapter 3 defines the goal and scope of a bridge LCA, including functional unit, system boundaries, and life cycle stages (A0–C4).
- Chapter 4 provides detailed guidance on life cycle inventory (LCI) data collection and treatment, including both generic and project-specific inputs.
- Chapter 5 provides recommended data and models to be used for LCI and LCIA specifically related to GHG intensity.
- Chapter 6 provides methodological guidance for estimating environmental impacts using life cycle impact assessment (LCIA) methods.

- Chapter 7 offers best practices for interpreting LCA results to support informed decision-making.
- Chapter 8 offers best practices for reporting LCA results to stakeholders.

  Chapter 9 contains appendices related to supplementary LCI data, sample data set and calculations, allocation methods and references to commonly used LCA tools.

Contents

1. Introduction and Background 1
1.1 Purpose of Assessment 1
1.2 Objectives 3
1.3 Structure 4
2. The Bridge System 7
2.1 Classification of Bridges 7
2.1.1 Function 7
2.1.2 Structure 9
2.1.3 The Bridge Elements 10
2.2 Life Cycle of a Bridge 11
2.3 Stakeholders 11
3. Goal and Scope 14
3.1 Objectives 14
3.2 Function (Primary and Secondary), Functional Unit, Alternatives, Reference Flows and Study Period 15
3.3 System Boundary 16
3.4 Life Cycle Modules 17
3.4.1 Pre-Construction Phase (A0) 17
3.4.2 Materials Production Phase (A1-A3) 20
3.4.3 Construction Phase (A4-A5) 20
3.4.4 Operation and Maintenance (use) Phase (B1-B8) 21
3.4.5 End-of-Life (EoL) – Decommissioning or Demolition Phase (C1-C4) 26
3.4.6 Beyond Life Cycle – Benefits and Loads (D) 27
3.5 Selection of Impact Categories and Impact Category Indicators 28
3.6 Defining the Interpretation Process 28
3.7 Data Quality Requirement 29
4. Life Cycle Inventory 30
4.1 Inventory Data 30
4.2 Unit Processes 31
4.3 LCI Workflow and Key Procedures 34
4.3.1 Preparing for Data Collection 36
4.3.2 Data Collection 37
4.3.3 Validation of Data 40
4.3.4 Relating Data to Unit Process and Functional Unit 41
4.3.5 Data Aggregation 42

4.3.6 Refining the System Boundary 43
4.3.7 Data Quality Assessment (DQA) 44
4.4 Documentation of LCI 47
4.5 Potential Pitfalls and Sources of Error 47
5. Life Cycle Impact Assessment (LCIA) 49
5.1 Mandatory Steps: Selecting Impact Categories, Classifying Indicators and Characterization Models 49
5.2 Optional Elements 51
5.3 Other Considerations 55
6. Data and Model Aspects 57
6.1 Quantifying the Bridge Data 57
6.1.1 Itemize the Bridge Elements 57
6.1.2 Obtaining Product Quantities 59
6.2 Models and Data Sources 59
6.2.1 Pre-construction (A0) 59
6.2.2 Material Production (A1 – A3) 60
6.2.3 Transport to Site (A4) 62
6.2.4 Construction and Installation (A5) 65
6.2.5 Use/Operation (B1) 70
6.2.6 Maintenance (B2) 72
6.2.7 Repair (B3) 75
6.2.8 Replacement (B4) 77
6.2.9 Rehabilitation (B5) 78
6.2.10 Deconstruction and Demolition (C1) 79
6.2.11 Transport of Waste (C2) 81
6.2.12 Waste Processing (C3) 81
6.2.13 Final Disposal (C4) 82
6.2.14 Beyond (D) 83
7. Interpretation 86
7.1 Key Factors for LCA Results Interpretation 87
7.2 Uncertainty and Sensitivity Analysis 88
7.2.1 Uncertainty analysis 88
7.2.2 Sensitivity Analysis 90
8. Reporting 92
8.1 Presentation of Results 92
8.2 Summary and Interpretation 92
8.3 Transparency and Stakeholder Communication 92

Reference **94**
9. Appendices **99**
9.1 Appendix A: Bridge Life Cycle Inventory Data 99
9.2 Appendix B: Dataset for Bridge LCI 100
9.3 Appendix C: Sample Calculations 103
9.3.1 Stage B (Phases B2-B5) 103
9.3.2 Equipment Energy Use Estimation (Applicable to All Life-Cycle Stages) 104
9.4 Appendix D: Allocation 105
9.5 Appendix E: LCA Tools and Software 108

List of Figures

Figure 1-1: Structure of this document 4
Figure 2-1: Life cycle of a typical bridge 11
Figure 2-2: Stakeholder's engagement required different levels and stages of an LCA study 12
Figure 3-1: Lifecyle stages and modules for Bridge Infrastructure Project LCA 19
Figure 3-2: Selected pavement characteristics and their impacts on use-phase objectives 23
Figure 4-1: The LCI analysis required by ISO 14044 for conformant LCAs 35
Figure 4-2: Steel production flow chart 39
Figure 4-3: Cement production flow chart 39
Figure 4-4: Example reference flows 43
Figure 4-5: Data quality scores in pedigree matrix 45
Figure 5-1:Classification and Characterization in ReCiPe mid-points 50
Figure 5-2: An example of process of attaining midpoint and endpoint impacts 51
Figure 5-3: An example of Characterized and Normalized Impact Categories 52
Figure 6-1: Itemize Bridge Element (Reinforced Concrete Pier) for Bridge Data Collection. Note: each element of the bridge will be expanded with related inventory details 58
Figure 6-2:CO2 Sequestrated by Trees Calculated for Different Tree Types and Period of Analysis 85
Figure 7-1: Distribution curves based on Zhang et al. (2016)92 90
Figure 8-1: Example illustration for LCA results of bridge,, ... 93
Figure 9-1: Conceptual illustration of partitioning and system expansion 105
Figure 9-2: Scope of the analysis of CO2NSTRUCT 110

List of Tables

Table 1-1: Canada's GHG emissions by economic sector in 2023 2
Table 2-1: Bridge type based on function 7
Table 2-2: Bridge type based on structure 9
Table 2-3: Examples of classification and coding of bridge components 10
Table 3-1: Types of system boundaries, strength, limitations and benefits 17
Table 3-2: Common bridge maintenance activities 25
Table 4-1: Inventory data categories 32
Table 4-2: Example of data collection planning 36
Table 4-3:Data collection methods 40
Table 5-1: TRACI 2.1 normalization factors for combined inventory of US and Canada with reference years 2008 and 2005 respectively 53
Table 5-2: Some common procedures for grouping of impact categories 54
Table 5-3: Numerical weight factors of ecological index method used in Bridge LCA study10 55
Table 6-1: Examples of LCI Data Requirements for Bridge Maintenance (B2) 73
Table 6-2: Examples of LCI data and data points for bridge repair (B3) 75
Table 6-3: Examples of LCI data requirements for bridge replacement (B4) 77
Table 6-4: Examples of LCI data requirements for bridge rehabilitation (B5) 78
Table 7-1: Statistical characteristics of weighted value of LCA impacts57 89
Table 7-2: Sensitivity of different pollutant discharges on LCA impacts57 91

List of Referred Guidelines and Standards

International Guidelines & Standards

- BS EN 17472:2022: Sustainability of Construction Works —Sustainability Assessment of Civil Engineering Works — Calculation Methods
- CEN/TR 16970:2016: Sustainability of Construction Works – Guidance for The Implementation of EN 15804. Technical Report. CEN
- EN 15978:2011: Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method. European Committee for Standardization (CEN)
- ILCD Handbook: International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment – Detailed Guidance. European Commission Joint Research Centre, 2010
- Infra2050 Bridges Working Group, Embodied Carbon of Bridges Guidance Document, 2025
- ISO 14040:2006: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization
- ISO 14044:2006: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization
- LCA4CCU-Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation, 2020
- PAS 2080:2023: Carbon management in buildings and infrastructure, BSI, 2023
- Technical Guidance - Embodied Carbon Measurement for Infrastructure. Infrastructure And Transport Ministers (Australia), 2024
- Net Zero Bridges Group Carbon Calculation Guide, 2024

Canadian Guidelines

- NRC's National Guidelines for Whole Building Life Cycle Assessment, National Research Council Canada, 2022
- National Whole-Building Life Cycle Assessment Practitioner's Guide, 2024

United States Guidelines

- Airfield Pavement LCA Guideline, 2016
- FHWA LCA Framework: Federal Highway Administration. Life Cycle Assessment Framework for Highway Infrastructure Projects, 2016

List of Acronyms

BoM	Bill of Materials
BrIM	Bridge Information Modeling
ECCC	Environment and Climate Change Canada
EIO-LCA	Economic Input-Output Analysis-based Life Cycle Assessment
EoL	End-of-Life
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
FHWA	Federal Highway Administration
FRP	Fibre-Reinforced Polymer
FU	Functional Unit
FUFs	Fuel Usage Factors
GHG	Greenhouse Gas
GHGRP	Greenhouse Gas Emissions Reporting Program
GWP	Global Warming Potential
ILCD	International Life Cycle Data
IRI	International Roughness Index
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCDM	Multi-Criteria Decision-Making Method
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NIR	National Inventory Report
NIST	National Institute of Standards and Technology
NRC	National Research Council Canada
NRMCA	National Ready Mixed Concrete Association

NUSAP	Numeral Unit Spread Assessment Pedigree
ODP	Ozone Depletion Potential
PCF	Pan-Canadian Framework
PCR	Product Category Rules
PM	Particulate Matter
PVI	Pavement–Vehicle Interaction
RCA	Recycled Concrete Aggregate
RSL	Reference Service Life
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UNFCCC	United Nations Framework Convention on Climate Change
USLCI	United States Life Cycle Inventory

Terms and Definitions (Glossary)

Activity Data

Quantitative measure of a process input or output (e.g., fuel consumed, material mass, transport distance) multiplied by an emission factor to calculate emissions.

Allocation

Partition of input or output flows of a process between the product system under study and one or more other product systems (ISO 14040)

Analysis Period

Time horizon over which life cycle impacts are assessed (e.g., 75-year bridge service life).

Background data

Data on processes or systems not directly controlled or influenced by the body performing the LCA but are necessary to complete the full life cycle picture

Bill of materials

The list of individual materials and products and their quantities that make up the physical asset

Byproducts

A secondary output of a process that is not the primary intended product but has economic value and can be used in subsequent applications without further waste treatment. If the by-product meets market specifications and is traded, it may require allocation procedures consistent with ISO 14044. If it displaces another product, system expansion may be applied.

Carbon dioxide equivalent (CO_2e)

Quantity of carbon dioxide that would be required to produce an equivalent warming effect over a given time period.

Category indicator

The unit used to measure the environmental impact.

Characterization factor

The contribution of an LCI result to the environmental impact relative to the equivalency unit for the category indicator

Characterization model

A mathematical representation of the relationship between life cycle inventory (LCI) results and environmental impact indicators in life cycle impact assessment (LCIA). For example, the Intergovernmental Panel on Climate Change's radiative forcing models

Completeness

A data quality metric that describes the degree to which all flow quantities within the assessment scope are included in the bill of flows.

Co-products

One of two or more products that are intentionally generated by a single unit process or product system and have economic value. When co-products occur, the system is considered multifunctional and the environmental burdens shall be allocated or addressed using system expansion in accordance with ISO 14044.

Cradle to gate

ime period from resource extraction through bridge product manufacturing. System boundary including product stage processes only, typically Modules A1–A3 (raw material supply, transport, and manufacturing), excluding construction, use, and end-of-life stages. (Aligned with EN 15804 modular structure and consistent with ISO 14044 system boundary requirements.)

Cradle-to-Site

System boundary including Modules A1–A4 (product stage plus transport to construction site), excluding installation and later stages.

Cradle-to-Installation

System boundary including Modules A1–A5 (product stage, materials transportation to site plus construction/installation processes).

Cradle to grave

Time period from resource extraction through end of life of bridge. System boundary including all life cycle stages from raw material extraction through end-of-life disposal (Modules A1–C4).

Data Quality Assessment (DQA)

Systematic evaluation of data used in an LCA study to determine its suitability in relation to the goal and scope, considering criteria such as temporal, geographical, and technological representativeness, completeness, consistency, and uncertainty.

Declared unit

Quantity of a construction product for use as a reference unit in an EPD based on LCA, for the expression of environmental information needed in information modules (ISO 21930:2017)

Elementary flow

A material or energy that enters or leaves the system being studied and interacts directly with the environment, without further human transformation

Embodied Carbon

GHG emissions associated with material production, construction, maintenance, and end-of-life stages (excluding operational traffic emissions, unless defined otherwise).

Emission Factor (EF)
Quantified value representing greenhouse gas emissions per unit of activity data (e.g., kg CO_2e per tonne of steel, per L of diesel, per kWh of electricity).

Environmental product declaration

A third party–verified document written in conformance with regional or international standards providing quantified environmental impacts data of a product using predetermined parameters and, where relevant, additional environmental information, based on life cycle assessment (LCA) models (ISO 21930:2017)

Flow

An input (quantity of product, energy or water) or output (quantity of waste) to the system boundary over the bridge life cycle

Foreground data

Data related to the processes that are directly controlled, influenced, or specific to the system being studied

Functional unit

Quantified performance function of a product system for a construction product or construction service used as a reference unit

Global warming potential

An environmental indicator used to describe the climate related environmental impacts of a product. It is a result and output of life cycle assessment (LCA), and expressed in terms of tonnes or kilograms of carbon dioxide equivalent (tCO2e or kgCO2e)

Goal of the LCA Study

Statement defining the intended application, reasons for conducting the study, target audience, and whether the results are intended for comparative assertions disclosed to the public. (Aligned with ISO 14040 and ISO 14044.)

Life cycle assessment

Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system, component, assembly, or bridge throughout its entire life cycle **Life cycle impact assessment**

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. The results may estimate “endpoint” impacts, such as damage to human health, or “mid-point” impacts, such as eutrophication

Life cycle inventory

A list of input and output flows for a particular process. The flows are resource use, such as materials, energy, and water, as well as emissions to air, land, and water

OmniClassTM

A comprehensive standardized classification system used in the construction industry, developed by the CSI in the United States. It is used to categorize and organize information related to construction projects, including, but not limited to, components, materials, systems, and processes throughout the whole project life cycle

Product category rules

Set of specific rules, requirements and guidelines for developing EPDs for one or more product categories

Pump-to-Wheel (PTW)

Life cycle stage covering the conversion of fuel or electricity into useful mechanical energy during vehicle or equipment operation. (Represents direct use-phase energy consumption emissions.)

Recycling

Reprocessing material at end-of life into new material

Reuse

Using component again without reprocessing

Reference Study Period (RSP)

Time span for which the system performance is assessed; typically aligned with the design service life in infrastructure LCA.

Scenario Analysis

Evaluation of alternative future conditions (e.g., traffic growth, maintenance intervals, electrification scenarios).

Scope of the Infrastructure LCA Study

Description of the methodological framework of the study, including system boundaries, functional unit, reference study period, allocation procedures, impact categories, data requirements, assumptions, limitations, and level of detail consistent with the study goal. (ISO-aligned definition adapted for infrastructure applications.)

Sensitivity analysis

A procedure in which selected input parameters or assumptions in a life cycle assessment (LCA) model are systematically varied, using deterministic values or defined distributions, to evaluate their influence on the LCA results.

Service life

Period of time after construction/installation during which an asset or facility or its component parts continues to meet the performance requirements

System boundary

The physical scope of assessment, including life cycle stages, building elements, processes, flows, and activities included or excluded from the life cycle assessment. It is the interface in the assessment between an asset and its surroundings or other product systems

Uncertainty analysis

A procedure to quantify the combined effect of uncertainty in input data, model structure, and assumptions on LCA results, typically using probabilistic methods.

Unit Process

Smallest element of a product system for which input and output data are quantified, representing a single operation or transformation within the life cycle.

Waste products

Any output from a process that the holder discards, intends to discard, or is required to discard, and which has no intended economic value at the point of generation. Waste flows are assigned environmental burdens associated with collection, treatment, recovery, or disposal processes. When waste undergoes recovery and becomes a usable material, its status in the product system shall be defined according to the applicable system boundary and allocation rules.

Well-to-Pump (WTP)

Life cycle stage covering extraction, processing, and distribution of a fuel or energy carrier up to the point of delivery to the vehicle or equipment. (Applies to fossil fuels and electricity; represents upstream energy production emissions.)

Well-to-Wheel (WTW)

Combined life cycle stage encompassing both Well-to-Pump and Pump-to-Wheel emissions, representing total energy-related emissions from production through end use.

1. Introduction and Background

1.1 Purpose of Assessment

This document provides guidance on the application of environmental Life Cycle Assessment (LCA) for bridge infrastructure in Canada. Its primary purpose is to support the quantification, interpretation, and reduction of greenhouse gas (GHG) emissions and other environmental impacts associated with bridge projects across their life cycle. This document is intended for stakeholders across the entire bridge construction value chain, including decision maker: bridge material producers and suppliers, bridge design engineers, bridge contractors and sub-contractors, bridge owners and asset managers, traffic managers and policy makers as well as LCA practitioners and LCA tool developers. The guidance is intended to be used at all stages of the bridge infrastructure lifecycle. In practice, LCA is used primarily as a planning and design tool, for example, to:

- Support early-stage material and design selection.
- Quantify and reduce embodied carbon and other environmental impacts.
- Compare alternative bridge designs, construction strategies, and materials.

During construction and maintenance, such as during construction or after completion, to document environmental performance, support reporting requirements, and evaluate the effectiveness of implemented strategies.

Municipalities and provincial transportation authorities may incorporate LCA-based recommendations into their procurement specifications or sustainability reporting, even when not mandated by law. By integrating LCA early in project development, stakeholders can identify opportunities to reduce embodied carbon and other environmental impacts while maintaining structural performance, safety, and cost effectiveness. At later project stages, LCA findings may inform strategies to reduce operational emissions or optimize repair schedules.

Canada endorses the scientific consensus of the international community that taking strong action to address climate change is critical and urgent. The Pan-Canadian Framework (PCF) on Clean Growth and Climate Change (2016)[1] is a step towards Paris Agreement target. PCF embodies a collective vision of clean economic growth through reducing anthropogenic GHG emissions and building resilience to climate change. Total Canadian GHG emissions are projected to be 742 Mt yr^{-1} in 2030 under the December 2016 emissions projections (based on Environment Canada and Climate Change, ECCC[2]) and Canada's target is 523 Mt yr^{-1} under PCF. Environmental life cycle assessment (LCA) is a powerful science-based tool for the identification and quantification of potential environmental impacts, such as GHG emissions of a product/service, over entire life cycle. In the broad context, LCA will be an indispensable tool supporting the Pan-Canadian approach that centers on pricing carbon pollution to achieve GHG emission reductions across all sectors of the economy.

[1] Environment and Climate Change Canada (ECCC) (2016). Pan-Canadian Framework on Clean Growth and Climate Change: Canada's plan to address climate change and grow the economy. ISBN 978-0-660-07023-0
[2] Environment Canada and Climate Change (ECCC) (2016). Canadian Environmental Sustainability Indicators: Greenhouse Gas Emissions.

The need to account and reduce GHG emissions is mirrored by Canada's national and international commitments. As a part of Annex I Party[3] to the United Nations Framework Convention on Climate Change (UNFCCC), Canada is committed to prepare and submit a national inventory of anthropogenic (human-made) sources and sinks of GHGs annually. Likewise, under Greenhouse Gas Emissions Reporting Program (GHGRP), Canadian facilities emitting 10,000 tonnes or more GHGs are required to report their annual GHG emissions. Since 2017, major sectors, such as aluminum, cement, iron and steel, lime, petroleum refining and others, are also required to report i) lowered threshold of facility emissions and ii) additional data reporting requirements and applying specific quantification methods to determine emissions[4].

Canada's GHG emissions from seven economic sectors are shown in **Table 1-1**. The transport sector is the second-largest GHG emitter after the Oil and Gas sector. However, the reported transport emissions primarily reflect operational emissions from passenger vehicles (cars, light trucks, aviation, buses, rail, and motorcycles) and freight movement (aviation, rail, marine, and trucks). Emissions associated with the construction, rehabilitation, and maintenance of transport infrastructure are not reported under the transport sector; rather, they are distributed across other sectors such as industry, energy, and manufacturing within the national inventory framework.

Table 1-1: Canada's GHG emissions by economic sector in 2023 (Mt CO_2 eq) [5]

Sector	Mt CO_2 eq	%
Oil and Gas	208	30%
Transport	157	23%
Buildings	88	13%
Heavy Industry	78	11%
Agriculture	70	10%
Electricity	49	7%
Waste and Others	50	7%
Total	694	100%

Built infrastructure is not only a major driver of Canada's economy but also a primary source of GHG emissions. In 2023, Canada's construction industry contributed roughly CAD 162 billion to the national economy (about 7.5 % of GDP) and was responsible for approximately 16.7 million tonnes of greenhouse gas emissions as construction activity expanded on infrastructure and other projects6. In response to growing infrastructure demands and the need to meet climate targets, Life Cycle Assessment (LCA) has emerged as a robust, quantifiable approach for evaluating environmental performance and supporting evidence-based decision-making. Consequently, its integration into codes, standards, and green rating systems is becoming increasingly common.

[3] All Annex I Parties, excluding the US, have participated in the 1st Kyoto commitment period. 37 Annex I countries and the EU have agreed to second-round Kyoto targets.
[4] Environment and Climate Change Canada (ECCC) (2025). Reporting greenhouse gas emissions data: technical guidance - Canada.ca
[5] Environment and Climate Change Canada (ECCC) (2025) https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/sources-sinks-executive-summary-2025.html
[6] Canadian Construction Association. (2024). Quarterly insights report Q4 2023: The construction industry and greenhouse gas emissions (p. 8). Canadian Construction Association. https://www.cca-acc.com/wp-content/uploads/2024/04/ICIC-Quarterly-insights-Q4-2023.pdf

Bridges play a critical role in Canada's transportation infrastructure, connecting communities, facilitating trade, and ensuring mobility across the country's vast and diverse landscape. There are more than 53,000 publicly owned highway bridges over 1 million kilometres of roads in Canada, ranging from small rural crossings to large urban structures and critical national corridors7. Many of these bridges are aging, with a significant proportion requiring maintenance, rehabilitation, or replacement in the coming decades.

Construction of bridge infrastructure requires large significant material, water, and energy inputs, resulting in GHG emissions. Likewise, bridges contribute to indirect emissions over activities related to service life such as maintenance, energy use, and traffic congestion. Structural materials degrade over time, requiring energy-intensive repair and replacement processes. Additionally, poorly maintained or congested bridges can increase fuel consumption and vehicle emissions due to delays and inefficient traffic flow, while other bridges may reduce transportation emissions from fuel consumption if they reduce the kilometres travelled. Hence, reduction of embodied carbon of bridges has become a key concern in the effort to reduce the environmental impact of infrastructure projects.

The integration of LCA in bridge design and construction is essential to quantifying and reducing embodied carbon and other environmental impacts. By assessing the full life cycle of a bridge—from material extraction and construction to maintenance and end-of-life scenarios. LCA can provide valuable insights to guide decision-making towards sustainable infrastructure solutions. LCA where the greatest sources of embodied carbon occur within the bridge system. This insight allows project teams to focus mitigation strategies on the most impactful components and processes. Importantly, LCA enables relative comparison between competing structural designs, material choices, and construction approaches, allowing designers and decision-makers to evaluate environmental performance alongside cost, durability, and safety considerations. Through such comparisons, LCA can highlight opportunities for carbon reduction, such as optimizing structural systems, reducing material quantities, increasing the use of lower-carbon materials (e.g., low-carbon concrete or recycled steel), and adopting construction methods that minimize energy and resource use while extending asset service life.

1.2 Objectives

The objective of this document is to establish a standardized framework and provide guidance for the LCA of highway bridges (Bridge LCA) in Canada. It aims to ensure consistency and quality in quantifying environmental impacts, particularly greenhouse gas (GHG) emissions, across all stages of bridge infrastructure, including design, construction, maintenance, repair, and end-of-life management. Specifically, this document seeks to:

- Introduce a standardized and consistent approach to Bridge LCA practice in Canada,
- Provide a framework to support the integration of LCA into the design of new bridges within the Canadian Highway Bridge Design Code (CSA S6),as well as into decision-

[7] Statistics Canada. (2022, May 24). Canada's Core Public Infrastructure Survey: Roads, bridges and tunnels, 2020. Government of Canada. https://www150.statcan.gc.ca/n1/daily-quotidien/220524/dq220524a-eng.htm

making for the maintenance, rehabilitation, strengthening, widening, and replacement of existing bridges;

- Encourage harmonization in Bridge LCA methodologies and tools, and
- Support LCA-based compliance schemes for greening Canadian infrastructure funding and policy frameworks.

1.3 Structure

The Guideline is organized into eight core chapters, each addressing a critical phase of the bridge LCA process.

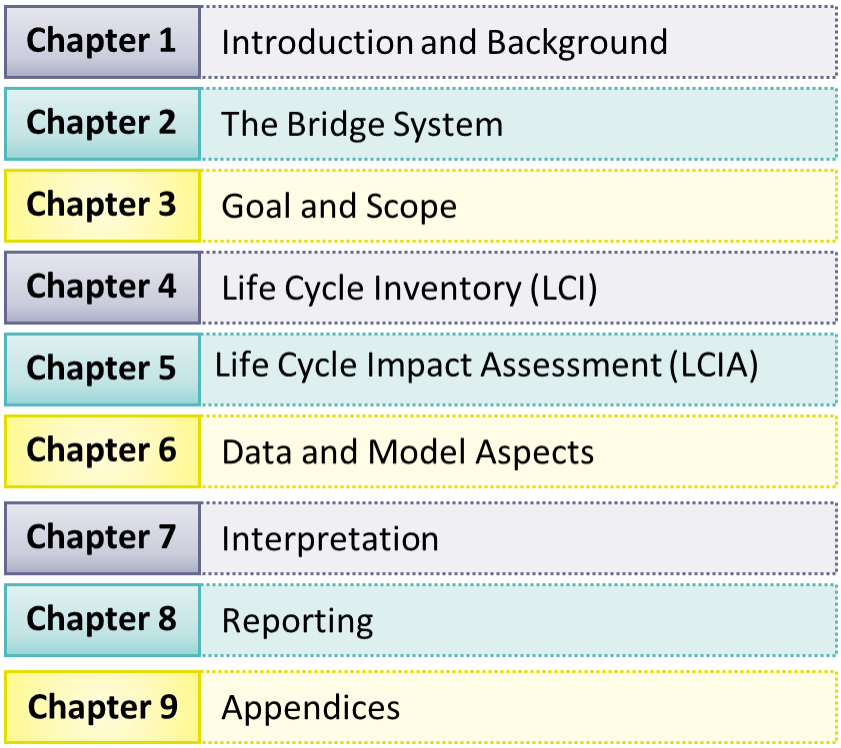


Figure 1-1: Structure of this document

Chapter 1: Introduction and Background

This chapter establishes the rationale and urgency for adopting LCA in Canadian bridge infrastructure. It outlines the environmental and policy drivers, the need for harmonized practices, and the benefits of LCA in informing low-carbon bridge design, material selection, and maintenance planning. It also positions the Guideline within the broader landscape of national and international standards.

Chapter 2: The Bridge System

This chapter provides an introduction to bridge systems, specifically

- Types of bridge systems and typologies considered (e.g., short-span girder bridges, cable-stayed bridges)

- Life cycle of bridge
- Stakeholder Engagement in the LCA Process

Chapter 3: Goal and Scope

This chapter defines how to structure an LCA study for bridges ensuring a consistent and comparable framework. Key components include:

- Purpose and intended application (e.g., design decision-making, policy compliance)
- Functional unit definition (e.g., 1 m² of bridge deck over the Reference Service Life)
- System boundaries, including cradle-to-grave processes (Modules A1–C4)
- Reference Service Life (RSL) assumptions

Chapter 4: Life Cycle Inventory (LCI)

This chapter offers methodological guidance for inventory analysis and outlines the processes of data collection, data analysis, and allocation. Additionally, it discusses the necessary documentation for Life Cycle Inventory (LCI) and highlights potential sources of errors that should be considered during inventory creation and analysis.

Chapter 5: Life Cycle Impact Assessment (LCIA)

This chapter explains how to translate LCI data into environmental impact indicators using established LCIA methods. It includes:

- Recommended impact categories, such as Global Warming Potential (GWP), Resource Use, and Eutrophication
- Preferred impact assessment methods, such as TRACI 2.2
- Temporal and spatial considerations, such as impact timing or regionalized emissions
- Guidance on consistent calculation, aggregation, and result interpretation to support comparability and decision support

Chapter 6: Data and Model Aspects

This chapter provides relevant data sources and models for of inputs and outputs across the bridge life cycle. Topics include:

- Preconstruction stage (A0)
- Material production and transportation (A1–A4)
- Construction and installation (A5)
- Use-stage activities such as maintenance, repair, replacement, and rehabilitation (B2–B5), including energy use for lighting or movable elements
- End-of-life processes including deconstruction, waste processing, and disposal (C1–C4)

- Recommendations for sourcing and documenting primary and secondary data, handling data gaps, and applying emission factors from national databases or EPDs.

Chapter 7: Interpretation

This chapter outlines best practices for interpreting LCIA results. This includes:

- Identification of environmental hotspots and sensitivity analysis
- Recommendations for visualizing results using charts, graphs, and tables

Chapter 8: Reporting

This chapter outlines best practices for communicating findings to the stakeholders. This includes:

- Transparent documentation of assumptions, data sources, and uncertainties
- Reporting formats suitable for both technical and non-technical audiences
- Support for policy reporting, funding applications, and design optimization

2. The Bridge System

This chapter provides an overview of common concepts related to bridge systems. This chapter describes common categories of bridge commonly found in Canada, followed by an overview of the typical life cycle of a bridge. Lastly the chapter enlist the various stakeholders required for conducting a successful life cycle assessment study on bridge infrastructure to ensure consistent comparisons between design and construction alternatives.

2.1 Classification of Bridges

Several types of bridges exist when performing LCAs. The bridge types can be categorized based on the function and/or structure. Lists (not exhaustive) of bridge types based on function and structure are presented in this section.

2.1.1 Function

Bridge function refers to the purpose and the method of use for a bridge. The function will ultimately impact the choice of structure, materials and lifespan. Common bridge types based on their function are provided in **Table 2-1.** Structural type, material system, and design life are treated as variables in alternative scenarios evaluated under a consistent functional definition.

Table 2-1: Bridge type based on function

Bridge Type	Description	Example in Canada
Road or highway	Designed and constructed to allow the movement of vehicles over obstacles like rivers, other roads, valleys and/or other infrastructure. May incorporate pedestrian, cycling, or wildlife passage elements.	Prince Edward Viaduct (Bloor Viaduct) in Toronto, ON
Railway	Designed and constructed to allow the movement of trains (passenger or freight) over obstacles such as rivers, valleys and other infrastructure like roads	Canadian National Railway Bridge in Red River, Winnipeg, MB
Taxiway	Designed and constructed to allow the movement of passenger planes	Taxiway R overpass, Toronto Pearson International Airport, ON
Wildlife Crossing (Ecological Connectivity)	Designed primarily to facilitate safe wildlife movement across transportation corridors, including overpasses and underpasses intended to maintain ecological connectivity.	Wildlife Overpasses, Banff National Park, AB

Pedestrian and cycling	Designed and constructed to allow the movement of pedestrians, cyclists or both over obstacles such as rivers, other infrastructure like roads, and valleys	Flora Footbridge in Ottawa, ON
Trail/ Snowmobile/ Recreational	Supports recreational trails, seasonal or all-year use, including snowmobiles or ATVs.	Quebec Snowmobile Bridge over Rivière Rouge, Quebec – supports winter recreational trail traffic.
Utility/Service	Bridges carrying utility pipelines, electrical lines, or service corridors; may be narrow, elevated, or integrated with pedestrian/maintenance access.	Pine River Utility Bridge, Ontario – supports water and electrical utilities across river.
Multi-Modal	Designed to accommodate more than one primary transportation mode (e.g., road and rail; road and pedestrian) as co-dominant functions.	High Level Bridge in Edmonton, AB

Note: Some Heritage bridges allow preservation of historic or cultural heritage routes. Heritage designation is not a functional bridge type but a status classification. Bridges of any functional category (road, rail, pedestrian, etc.) may have heritage designation, which may influence rehabilitation, material selection, and LCA boundary assumptions.

2.1.2 Structure

Bridge structures carry loads from traffic, utilities, and environmental forces to the foundation. Common structural types are listed in **Table 2-2**.

Table 2-2: Bridge type based on structure

Bridge Type	Description	Example in Canada
Beam (Girder)	Horizontal beams or girders that support the bridge deck	Queensborough Bridge in New Westminster, BC
Arch	Based on arch design and load transfer through compression, includes deck arch, through arch, tied arch and network arch.	Humber Bay Arch Bridge in Toronto, Prince Edward Viaduct (Bloor Viaduct), Toronto, ON
Segmental	In this bridge type, precast or cast-in-place segments are joined together, often post-tensioned; suitable for medium to long spans and rapid construction	Don Valley Parkway Bridges, Toronto, ON
Suspension	In this bridge type, the deck is suspended from cables supported by towers; Deck hung from cables anchored at ends and draped over towers; suitable for very long spans.	Lions Gate Bridge in Vancouver, BC
Cable-stayed	In this bridge type, Deck is supported directly by cables connected to towers; efficient for long spans and heavy loads.	Champlain Bridge in Montreal, QC
Truss	A Truss bridge carries the load in axial tension and compression within its members	Canso Causeway Bridge in Nova Scotia
Cantilever	In this bridge type, the structure is supported only at one end of the bridge	Quebec Bridge in Quebec City, QC
Floating (pontoon)	This bridge types, are floated on water using barges or pontoons	Bow River Floating Bridge in Calgary, AB
Moveable	This bridge types can be moved, for example, rotated or raised for boats or ships to pass.	The Burlington Canal Lift Bridge in Burlington, ON
Frames	Structural system where load is carried through interconnected beams and columns in bending and axial forces.	The Pont Joffre Bridge in Sherbrooke, QC

2.1.3 The Bridge Elements

Bridge elements are the discrete components that make up a bridge structure. **Table 2-3** provides examples linking OmniClass coding to ISO classification to illustrate how bridge components can be systematically categorized for asset management and LCA purposes"[8]. The table includes major superstructure, substructure, and deck system components to guide consistent identification of materials and processes during life cycle assessment.

Table 2-3: Examples of classification and coding of bridge components[6]

Code of components	Types of bridges	Bridge parts	Subparts	Component
03-01.00.00.00	Beam bridge			
03-01.01.00.00	Beam bridge	Superstructure		
03-01.01.01.00	Beam bridge	Superstructure	Bridge girder	
03-01.01.01.01	Beam bridge	Superstructure	Bridge girder	Concrete box girder
03-01.01.01.02	Beam bridge	Superstructure	Bridge girder	Concrete t-beam
03-01.01.01.03	Beam bridge	Superstructure	Bridge girder	Solid plate girder
03-01.01.01.04	Beam bridge	Superstructure	Bridge girder	Hollow slab beam
……				
03-01.01.02.00	Beam bridge	Superstructure	Bridge bearing	
03-01.02.00.00	Beam bridge	Substructure		
03-01.03.00.00	Beam bridge	Bridge deck system		
……				
03-02.00.00.00	Truss bridge			
03-03.00.00.00	Arch bridge			
03-04.00.00.00	Cable-stayed bridge			
……				

[8] Hu, S., Ma, W., Zhu, Y., & Cong, L. (2023). Research on Information Coding and Management for Big Data Mining in Highway Bridge Operation and Maintenance. In 2023 3rd International Conference on Public Management and Intelligent Society (PMIS 2023) (pp. 1090-1097). Atlantis Press. https://doi.org/10.2991/978-94-6463-200-2_115

2.2 Life Cycle of a Bridge

The concept of sustainability in bridge has been introduced in 2019 Canadian High Bridge Design Code (CHBDC) and the later versions are aimed to include LCA[9]. According to the CHBDC the bridge should be a designed for a minimum of 75 years design life (**Figure 2-1**). While we may construct for a 75-year service life, this does not mean that bridges are retired and replaced after they reach 75 years. Some bridges will often last beyond 75-years and may undergo significant maintenance program to extent their useful life far beyond their initial designed life. Likewise, major repair/rehabilitation of bridge can take less or more than 30 years depending upon the type of bridge, its usage and the local environmental conditions. The life cycle of bridge infrastructure encompasses several key phases: planning, design, material production and procurement, construction, operation and maintenance, rehabilitation, and end-of-life (which may involve demolition, reuse, or recycling). Each of these phases contributes to environmental impacts, particularly in terms of carbon emissions. The most significant sources of carbon emissions typically arise during the production and transportation of construction materials such as cement, steel, and asphalt. Construction activities, including machinery use and on-site operations (e.g., fugitive emissions from on-site welding), also contribute to greenhouse gas emissions. During the operational phase, maintenance work and vehicle use at the bridge can add to the environmental footprint. Conducting an LCA across the full life cycle of a bridge enables comprehensive accounting of environmental impacts. The level of detail and system boundaries applied, however, depend on the study objective and available data, which vary according to the bridge's life cycle stage; including design, construction, operation, maintenance and rehabilitation, exposure to site-specific hazards (e.g., seismicity or flooding), and end-of-life scenarios.

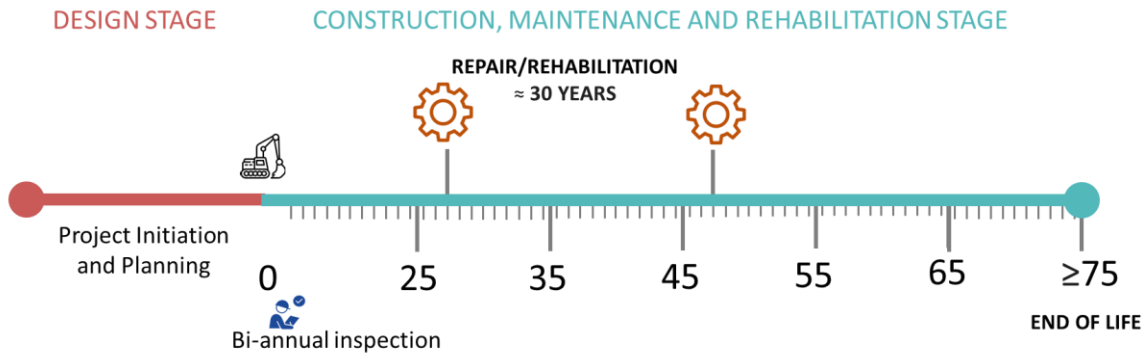


Figure 2-1: Life cycle of a typical bridge

2.3 Stakeholders

Conducting an LCA of bridge infrastructure is a complex process that involves input and collaboration from multiple stakeholders. **Figure 2-2** shows the different stakeholders who need to be engaged or serve as data sources during the LCA process. Data for the study comes from internal and external sources to the project. Internal stakeholders include the parties directly

[9] CSA. (2019). Canadian highway bridge design code (CSA S6-19). CSA Group

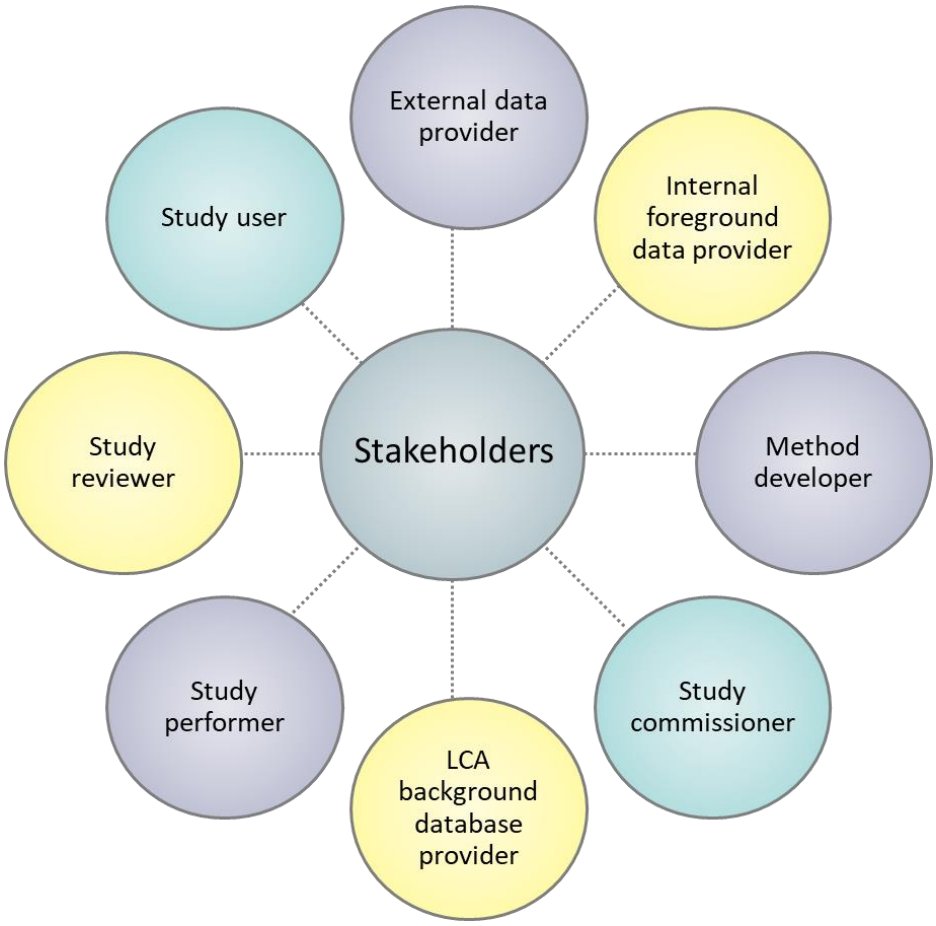


Figure 2-2: Stakeholder's engagement required different levels and stages of an LCA study[10]

involved with the project under design and construction. Project managers, site engineers, maintenance teams, and procurement teams are examples of internal stakeholders. External stakeholders, on the other hand, can include material suppliers and industry associations, among others. LCA method developers are mostly from academia and are the main sources of robust, validated LCA methods. The study commissioner may be the organization or association requiring the study to be conducted, such as policymakers. LCA background data providers are LCA database suppliers (such as Ecoinvent and Sphera Managed LCA Content (MLC)) required to provide background data, such as life cycle inventories and emission factors of materials and processes. Study users are the individuals or organizations applying the LCA results for decision-making, such as optimizing design, material selection, or maintenance strategies.

[10] Ramirez, A.R., Khamlichi, A. E., Markowz, G., Rettenmaier, N., Baitz, M., Jungmeier, G., Bradley, T. (2020). LCA4CCU Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation. https://doi.org/10.2833/161308

The LCA study can be conducted by a qualified LCA practitioner, either internally or through a consultant with expertise in environmental life cycle analysis. To validate the results and ensure the project goals are achieved, an external reviewer may be engaged. The final decision-making team, including design engineers, bridge owners, and policy makers, integrates LCA findings into material selection, design, and construction decisions.

Stakeholder engagement at each LCA stage ensures that:

- Background and foreground data are clearly distinguished. This
    - Foreground data refers to information that is directly related to the bridge project under study and is under the control or influence of the bridge owner. This includes data on material quantities, construction methods, maintenance schedules, and operational conditions. Background data refers to generic or industry-wide data, typically obtained from LCA databases (e.g., Ecoinvent, GaBi Sphera Managed LCA Content), which provide information on upstream processes such as material production, transport, and energy generation;
    - The classification of data as foreground or background depends on who is conducting the LCA. For example, from the bridge owner's perspective, foreground data is primarily data that the bridge owner can provide or influence, while background data comes from external sources beyond their direct control. Clarifying this distinction ensures that the bridge owner understands which data can be reliably managed and where assumptions or secondary data may need to be used.
- Study objectives and assumptions align with the functional requirements of the bridge.
- Planning, construction, and maintenance decisions incorporate environmental considerations alongside cost, safety, and durability.

3. Goal and Scope

In the context of construction of sustainable bridges, the design of a bridge goes beyond the traditional requirements of safety and initial costs. The life cycle approach requires the analysis of environmental aspects of the entire life cycle of bridges, including *"planning and design, material provision, construction, maintenance and rehabilitation, end of life, and transportation in all phases. Missing a life cycle phase may result in suboptimal decisions*"[11].

It is crucial to start by defining the right questions that we would like to be answered regarding the environmental assessment of bridges. Horvath (2009)[8] states that in the case of bridges, questions might deal with:

- Exploring alternative materials (steel, concrete, FRP, or wood) for bridge components (e.g., girders)
- Comparing bridge designs (e.g., if cable-stayed bridges are more environmentally friendly than suspension bridges)
- Reducing the overall environmental burden of constructing a particular bridge or bridge type, or even larger, network-type questions, e.g., if we should tunnel or build a bridge or build a long road around a natural barrier.

In the following sections, the goal definition (including objectives, function, functional unit and system boundary), and scope (including life cycle modules, allocations, impact categories and interpretation process) for performing a bridge LCA is provided.

Goal and Scope form first phase of an LCA study. The Goal outlines the purpose of the study and identifies its intended audience, while the Scope specifies the system boundaries, functional unit, data requirements, and assumptions that guide the assessment. According to ISO 14040:2006[12], "*the scope of the LCA study should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal*." Some of the common items to be included as part of scope based on ISO 14044:2006 and International Reference Life Cycle Data System (ILCD) Handbook are: Description of product/system under study; Objectives; Function(s) and functional unit; System boundary; Allocation Procedure; LCIA methodology and specific environmental impacts; Assumptions and Limitations.

3.1 Objectives

The objective for bridge LCA studies is usually to evaluate the environmental impacts throughout bridge's life cycle. Defining clear robust objectives support decision-makers, bridge designers and engineers, and LCA practitioners to make informed decisions related to design, construction, operation and maintenance, and decommissioning phases. Depending on the project, objectives

[11] Horvath, A. (2009). Principles of using life-cycle assessment in bridge analysis. In Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials, Sapporo, Japan, October (pp. 21-22).
[12] Arvanitoyannis, I. S. (2008). ISO 14040: life cycle assessment (LCA)–principles and guidelines. Waste management for the food industries (pp. 97-132). ISBN: 9780123736543

for bridge LCA studies can be one or more of the following aspects (the list is not exhaustive):

- To quantify the environmental impacts and identify hotspots (e.g., for embodied or operational GHG emissions, or resource use, etc.) over the entire life span of a bridge.
- To assess and compare different bridge design alternatives (structural systems and materials) from an environmental perspective without compromising safety, functionality or cost.
- To evaluate the circularity (e.g., design for disassembly) and potential for repurposing, reusing or recycling of bridge elements and materials.
- To identify solutions that improve the durability and resilience of bridge elements, components, and the overall asset, thereby reducing the need for maintenance and repair activities and minimizing life-cycle environmental impacts and potential service disruptions.
- To meet regulatory requirements and compliance with environmental standards, regulations and certifications such as Envision or Greenroads.
- To increase awareness and enhance understanding of life cycle environmental impacts of bridges and potential opportunities and benefits of sustainable infrastructure practices.

3.2 Function (Primary and Secondary), Functional Unit, Alternatives, Reference Flows and Study Period

In Bridge LCA, the definition of the function, functional unit, alternatives, reference flows and study period are fundamental modelling parameters. These elements establish the basis for system boundary definition, inventory modelling, and, where applicable, the standardized comparison of alternative bridge designs or construction approaches.

The ***function*** of the bridge defines the context for the LCA study and help define the assessment scope and impact categories. The primary function of bridges is providing safe and accessible routes over obstacles such as railways, highways, rivers or connecting two land areas for example over a valley in accordance with applicable design standards adn safety requirements. Bridges may also deliver secondary functions, including facilitating economic activity, improving accessibility to communities, supporting goods movement, and enabling access to cultural or recreational destinations. While secondary functions provide contextual relevance, the functional unit for comparative LCA should be based primarily on the core structural and transportation function.

The ***functional unit (FU)*** is used to provide a reference point on which inputs and outputs are related and is essential to compare LCA results of different systems. It ensures a standardized comparison between different designs or types of bridges enabling a consistency of the LCA study results. The functional unit for Bridge LCA should quantify the performance of the bridge system being studied, including the level of service delivered and the duration of that service, to ensure comparability of LCA results across alternatives. In comparative assessments, the FU must reflect equivalent load capacity, design standards, and service life to avoid bias in results. FU should

include technical and functional requirements, patterns of use and study period. As an example of pedestrian bridge the FU can be defined as: allowing pedestrians to cross the ditch for 100 years[13]

Based on the bridge LCA study objective/s, ***alternatives*** can be defined to evaluate their environmental impacts in order to choose the most sustainable option. Types of alternatives can be based on structural design (e.g., beam, arch or cable-stayed bridges), materials (e.g., concrete, steel, composites, FRP (fibre-reinforced polymer)), construction approach (e.g., cast-in place concrete or pre-cast segments in modular construction), and maintenance methods and strategies (e.g., using more durable and low-maintenance materials and components).

The ***reference flow*** is the quantifiable amount of product required to fulfill the intended function. For bridge reference flow is the amount of product or service needed to meet bridge function over its entire life cycle. Reference flow is used as the basis for the calculation of environmental impacts (e.g., embodied carbon) per unit of service during the LCA study. It is essential for normalization and consistent comparison of environmental impacts of different bridge alternatives. Reference flow is dependent on the functional unit. Example of reference flow can be 10 m^3 concrete for bridge piers or number of vehicles per year (vehicle-kilometers traveled).

The ***study period*** in life cycle assessment, including in Bridge LCA, needs to be considered at the beginning of the study as it has a direct impact on data requirements and modelling, the environmental impact results and interpretation. It is the total period of time (duration) during which the environmental impacts of a bridge alternative are assessed and reported. It is usually similar to the bridge design or service life but can vary depending upon the LCA purpose, regulatory requirements or change in climatic conditions. CAN/CSA S6[14] specifies that bridges are designed for a service life of 75 years. LCA study period for bridge needs to consider a number of factors, including but not limited to design/service life, potential functional changes, different material durability ranges, and regular or planned maintenance intervals. When alternatives have different design lives, impacts shall be normalized to a common study period or replacement assumptions shall be explicitly modelled to ensure equivalence. Key considerations include:

- Planned maintenance and rehabilitation intervals
- Replacement of major components (e.g., deck replacement)
- End-of-life treatment assumptions

The study period and associated boundary conditions should be transparently documented.

3.3 System Boundary

The definition of system boundary is important because it ensures all critical stages of a bridge life cycle are taken into account and less impactful or irrelevant stages are phased out. The stages to consider along the bridge's life cycle are material production, construction, maintenance and

[13] Deschamps, J., Tagnit-Hamou, A., Fournier, B., & Amor, B. (2021). Assessing the Environmental Benefits of Using Glass Powder as a Supplementary Cementitious Material in a Context of Open-loop Recycling.
[14] CSA S6:19 (2019). Canadian Highway Bridge Design Code. Canadian Standards Association Group.

use, rehabilitation, and end of life (EoL). These can be translated to similar the lifecycle models as defined by the NRC National Whole Building LCA Guidelines:

- cradle to grave (raw material extraction to demolition/disposal),
- cradle to gate (i.e., factory gate),
- gate to gate (limited to the manufacturing process), and
- cradle to cradle, which includes the EoL stage and is in line with the circular economy approach.

The processes implied in these stages must be taken into account in planning and design (pre-construction phase), which includes project conception design, structural design and material selection. System boundaries have direct impact on the LCA results. Details on different modules associates with life cycle of an infrastructure are explained in Section 3.4. This modular approach of conducting LCA is adapted from EN 17472:2022 and PAS2080:2023. Modular approach enables more efficient handling of data, reduced modelling effort, flexibility of users in excluding/including processes and comparing alternative scenarios and their impact throughout the life cycle of product/system under study. These modules also enable creation of structured and reusable components that are scalable and adaptable with change in material, energy or technologies. LCA can be applied to one or more phase of bridge life cycle depending upon requirements of stakeholders. Selecting limited boundaries, example focusing only on production phase A1-A3, carries the risk of burden shifting from one phase to another. Common system boundaries adopted in literature and their application, strengths and limitations are provided in **Table 3-1**.

3.4 Life Cycle Modules

Processes involved in life cycle of a bridge can be broadly grouped under two categories: design and construction, maintenance and rehabilitation stages. **Figure 3-1** shows major life cycle stages and processes included within the scope of bridge LCA analysis.

3.4.1 Pre-Construction Phase (A0)

All processes related to design stage are part of pre-construction Module (A0) of LCA. It includes all activities before the physical construction starts such as preliminary studies, land acquisition and design. In case of buildings LCA, the impacts of Phase A0 can be considered negligible for buildings and often excluded from scope of building studies. However, they can become significant for infrastructure projects, such as bridge LCA. BS EN 17472: 2022[15] standard provides concept of Module A0 for assessing environmental impacts of civil engineering works. Likewise, Royal Institution of Chartered Surveyors (RICS)[16] recommend considering impacts of this phase for infrastructure projects when significant. Inclusion of this phase can provide a more holistic picture of life cycle environmental impacts of bridge infrastructure.

[15] BSI. (2022). BS EN 17472: 2022. Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods.
[16] RICS (2023) Whole Life Carbon Assessment for the Built Environment, RICS Professional Standard, 2nd edition, Whole Life Carbon Assessment for the Built Environment, RICS Professional Standard, 2nd edition - RICS iConsult. https://consultations.rics.org/whole_life_carbon_standard/viewCompoundDoc?docid=13626324&partId=13629428.

Table 3-1: Types of system boundaries, strength, limitations and benefits

Life Cycle Phases	Description	Strengths	Limitations	Stakeholders
A1–A3	Includes raw material extraction, processing, and production	Compared to other stages data acquisition is easier in form of Bill of materials, Drawings, and published EPDs; and can closely reflect realized emissions associated with upstream material production and sourcing.	Ignores transport, construction, use, maintenance, and end-of-life impacts.	Material suppliers, policymakers (example procurement policies)
A1-A5 (As-Built)	Includes material production (A1–A3), transportation of materials to the construction site (A4), and construction and installation processes (A5), including equipment use, temporary works, and construction waste.	Captures the full embodied carbon associated with bridge construction, including material production, transportation logistics, and on-site construction activities. Results are particularly useful for early design comparisons and procurement decisions where operational impacts are expected to be relatively similar between alternatives.	Does not capture impacts associated with the use, maintenance, rehabilitation, and end-of-life phases, which can be significant for long-lived bridge infrastructure.	Bridge designers, contractors, procurement authorities, infrastructure owners (e.g., MTO, MTQ, municipalities).
B1–B7	Focuses solely on the bridge's performance during its operational life	Identifies hotspots during bridge operation and maintenance stage	Major impacts related to material production and construction are missed	Transport Engineers and bridge operation and maintenance authority (example MTO, Indigenous Services Canada)
A1–A5 + B1–B7 + C1–C4 (Whole Life Cycle)	Environmental impacts associated with whole bridge life cycle	Provides comprehensive analysis that allows long-term planning and emissions optimization over lifespan	Requires detailed data and long-term assumptions regarding maintenance schedules, service life, and end-of-life scenarios; which can introduce uncertainty and increase modeling complexity	Bridge owners, policy-makers, LCA researchers
A1–A5 + B1–B7 + C1–C4 +D	Includes the full bridge life cycle plus benefits and loads beyond the bridge's life, such as reuse, recycling, energy recovery, and carbon sequestration from materials or landscape elements	Captures both environmental burdens and potential benefits; supports circular economy assessment and long-term sustainability planning	Even more data-intensive and complex; requires assumptions about future reuse, recycling rates, and potential environmental credits, which can add uncertainty	Bridge owners, policy-makers, sustainability analysts, LCA researchers, contractors interested in circular economy benefits

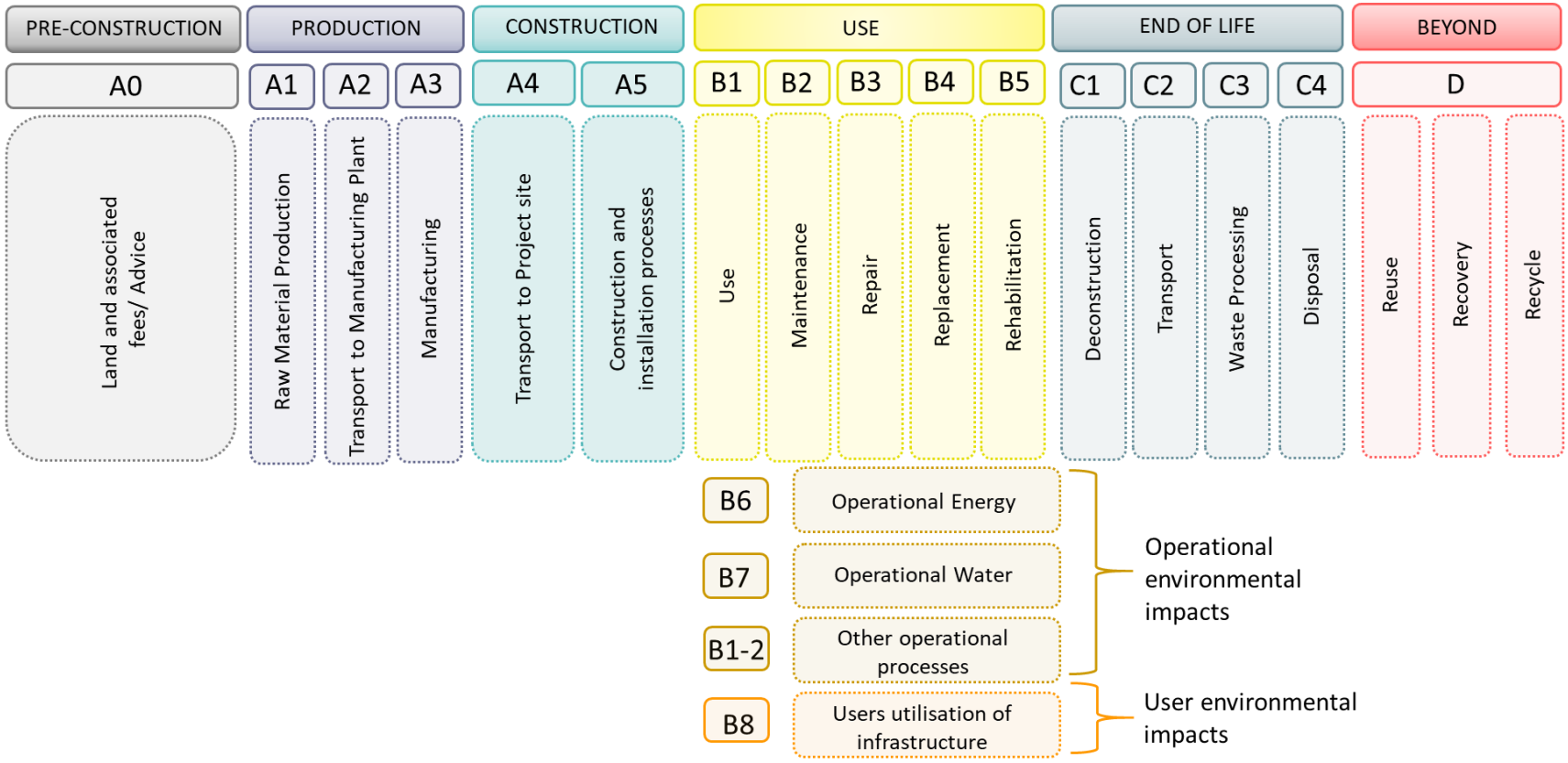


Figure 3-1: Lifecyle stages and modules for Bridge Infrastructure Project LCA[17]

[17] BSI. (2022). BS EN 17472: 2022. Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation method

Typical A0 activities may include: geotechnical investigations (drilling, sampling, laboratory testing)

- site surveys and field inspections
- engineering design activities
- project coordination meetings and travel.

3.4.2 Materials Production Phase (A1-A3)

At this stage, raw and processed (manufactured) materials to be used in construction (e.g., steel, concrete, asphalt) and the energy required to extract, process and manufacture such materials are evaluated.

The material production stage includes:

- Extracting natural resources (e.g., quarrying of aggregates, mining of ores)
- Processing and refining (e.g., clinker production, steel billet manufacturing)
- Manufacturing and formulating materials (e.g., batching of concrete or hot mix asphalt)
- Manufacturing and fabrication of precast product and structures (e.g., deck panels, deck slabs, girders, piers, other super structure and foundation components)
- Transporting and storing internally from manufacturer's gate up to the product's point of exit

Exclusions: Temporary storage, downstream packaging, and off-site construction logistics are outside the A1–A3 system boundary and must be accounted for in subsequent modules.

3.4.3 Construction Phase (A4-A5)

During this phase, environmental impacts at bridge construction stage including but not limited to material transportation to site, components assembly, machinery and equipment energy consumption and associated emissions are taken into consideration.

3.4.3.1 *Module A4-Transportation of Products to the Construction Site*

Module A4 covers the environmental impacts associated with the transportation of construction products and materials from the point of manufacturing to the bridge construction site. This includes direct fuel combustion as well as upstream emissions from fuel production and delivery.

Some key factors to be considered here include:

- Include emissions only up to the point-of-entry to the bridge construction site
- Exclude off-site storage, laydown yards, or transshipment points, unless they are integral to the material delivery function
- Where multiple materials are transported together, allocate emissions based on mass, volume, or economic value, and document the chosen allocation method

3.4.3.2 *Module A5-Construction and Installation Stage*

The Construction and Installation stage (Module A5) captures environmental impacts associated with on-site activities required to construct the bridge. This includes direct energy and fuel use, construction processes, ancillary materials, and waste generation and management. A5 typically occurs over a defined project timeline and is a key contributor to total embodied carbon, especially for energy-intensive operations and high-waste scenarios. This module ends when the bridge is ready for use and transitions to the operational phase.

This Module includes all activities and temporary works required to complete the bridge installation, such as:

- Mobilization and demobilization of equipment
- On-site construction processes (e.g., lifting, placing, pouring)
- Operation of heavy machinery (e.g., cranes, pumps, excavators)
- Use of temporary facilities (e.g., site offices, lighting, sanitation)
- Application of curing agents, coatings, and formwork
- Site-generated waste and its handling (e.g., recycling, landfill)

Landscaping: For the purposes of bridge LCA, landscaping features such as roadside slopes, embankments, and vegetated retaining walls may be included within the system boundary if they are constructed, maintained, or functionally integrated with the bridge asset. Although not part of the structural components (e.g., superstructure or substructure), these areas can contribute to environmental impacts and benefits, especially in land use, biodiversity, stormwater management, and carbon sequestration. Vegetated retaining walls, planters, bioswales, and similar green features offer both functional and ecological value, including erosion control, pollutant reduction, habitat creation, and aesthetic enhancement. While typically small in scale, these elements can support project goals such as urban heat mitigation and visual integration, even if not always quantified in the LCA. The inclusion of landscaping elements must be justified in the goal and scope section, considering design integration, ownership, and data availability. Landscaping may be implemented post-construction and should be captured within the project boundary if relevant to the asset's life cycle impacts. Landscaping construction may occur post-bridge commissioning and can be part of municipal or community improvement projects—define project boundaries accordingly. In addition, any change in land use due to bridge project that can result in land use and land use change impacts should also be evaluated for Module A5.

3.4.4 Operation and Maintenance (use) Phase (B1-B8)

Environmental impacts of a bridge over its operational life related to weather exposure, traffic loads, and required repairs or maintenance, such as surface reinstatements or repainting of metallic elements, are considered in this phase. Over the service life, bridge inspection is necessary, and its intensity and frequency may vary considerably based on the climate conditions, economic resources, daily traffic flow, and prioritization strategies.

3.4.4.1 *Module B1-Use Phase*

Includes impacts that occur during the normal use of the bridge without any replacement or active maintenance, such as:

- Leaching of materials from concrete surfaces (e.g., calcium hydroxide, admixtures corrosion products, heavy metals from weathering steel)
- Leaching of substances from steel surfaces (e.g., corrosion products, admixtures)
- Runoff-related environmental impacts (e.g., contaminated water runoff from the deck)
- Noise, vibration, or emissions to surroundings (e.g., for movable bridges or highly trafficked corridors)
- Surface wear and particulate emissions from vehicle contact
- Pavement–Vehicle Interaction (PVI): increased fuel/energy use due to surface roughness, deflection, and texture of the bridge deck pavement. PVI impacts on fuel consumption and CO2 emissions are generally small for typical bridges but can become significant for long-span bridges (e.g., Confederation Bridge) where deck roughness and deflection can measurably influence vehicle fuel use.
- Criteria Air Pollutant (CAP) emissions from traffic: Emissions associated with vehicle use at the bridge include not only greenhouse gases (GHGs) but also criteria air pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM_{10} and $PM_{2.5}$), and other tailpipe emissions. These pollutants can have significant impacts on local air quality and human health, particularly in urban or high-traffic corridors. Unless traffic consists entirely of zero-emission vehicles, CAP emissions should be considered where relevant and where data are available
- Carbon sequestration from landscaping on and round the bridge structure
- Carbon sequestration due to concrete carbonation over the bridge service life
- Heat island effect depending on the type of material used for the surface overlay

As pavement is a significant part of highway bridges, the environmental impacts associated with Use Phase, are mainly the ones related to the period when the pavement is in service and in interaction with vehicles and the surrounding environment. For example, the pavement roughness affects the vehicle fuel consumption as well as the noise resulting from tire-pavement interaction. Some pavement characteristic and their impacts on pavement's use phase are shown in **Figure 3-2** (Adapted from the FHWA's Pavement LCA Framework[18])

It should also be noted that there is still great uncertainty on Use Phase impacts, as many of these impacts are not yet well quantified.

Other Impacts and Processes in Bridge Use Phase include, but are not limited to:

[18] Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., & Kendall, A. (2016). Pavement Life Cycle Assessment framework (No. FHWA-HIF-16-014). United States. Federal Highway Administration.

- Energy Use for Movable Bridges

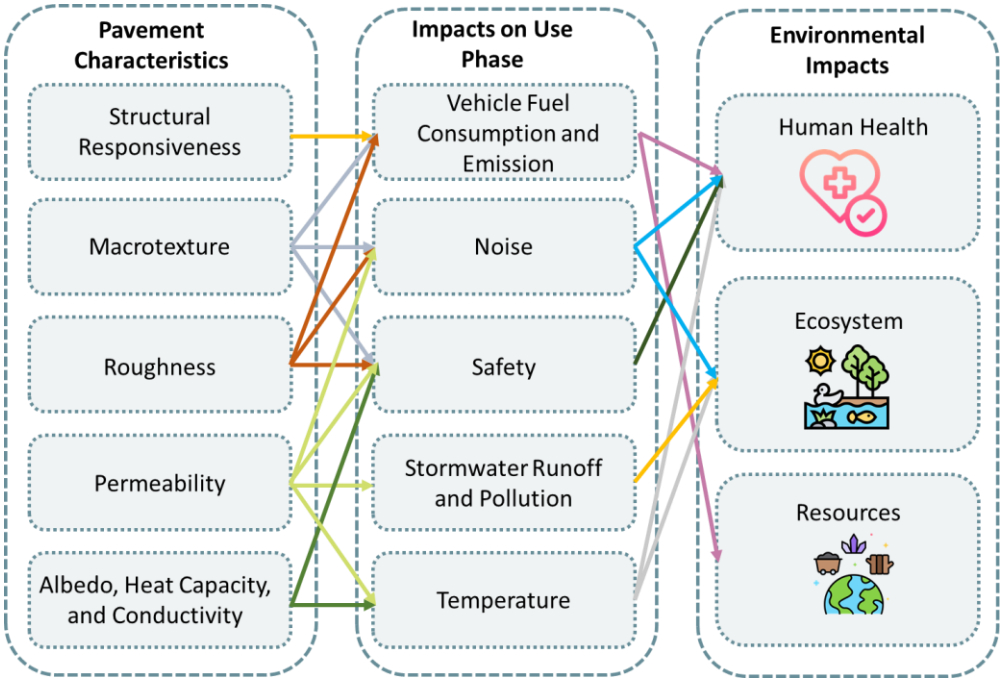


Figure 3-2: Selected pavement characteristics and their impacts on use-phase objectives[19]

- Drainage and stormwater runoff (including pollutants such as rubber, oil and heavy metals)
- Heat island effect (in dense urban areas)
- Noise pollution
- Vibration impacts

In addition to aesthetic and ecological functions, landscaping elements on or near bridge infrastructure can play a role in carbon sequestration during the use stage. Vegetation such as trees, shrubs, and groundcover plants absorb atmospheric carbon dioxide (CO_2) through photosynthesis and store it in biomass and soil, thus contributing to climate change mitigation. This sequestration potential is particularly relevant for green infrastructure and bridge projects incorporating vegetated medians, planters, embankments, green walls, or bioswales. The sequestration benefit of this practice will depend on some key considerations:

- Vegetation Type: The sequestration rate depends heavily on the species planted. Woody plants such as trees and shrubs generally sequester more carbon than grasses and perennials.
- Planting Density and Maturity: Higher planting density and longer growing periods increase

[19] Van Dam, T. J., J. T. Harvey, S. T. Muench, K. D. Smith, M. B. Snyder, I. L. Al-Qadi, H. Ozer, J. Meijer, P. V. Ram, J. R. Roesler, and A. Kendall. (2015). Towards Sustainable Pavement Systems: A Reference Document. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC

the cumulative carbon sink potential. Newly planted vegetation sequesters less carbon initially compared to mature landscapes.

- Soil Carbon Storage: In addition to biomass, soil can store significant amounts of carbon through organic matter accumulation. Practices such as compost application and reduced disturbance (e.g., avoiding soil compaction) can enhance this storage.
- Maintenance Practices: Minimal use of fossil-fuel-powered equipment, use of organic mulching, and optimized irrigation contribute to maximizing net carbon sequestration by reducing emissions associated with landscape upkeep.

3.4.4.2 *Module B2-Maintenance (Routine & Preventive)*

Covers routine maintenance activities that do not replace structural components, such as:

- Joint sealing and reapplication of coatings
- Cleaning and debris removal
- Painting railings and other superstructure elements
- Sandblasting
- Use of de-icing salt
- Waterproofing
- Minor pavement surface treatments
- Corrosion protection measures
- Electrical systems maintenance
- Riprap maintenance
- Routine bridge inspections

3.4.4.3 *Module B3-Repair*

Encompasses localized repairs due to damage or deterioration, including:

- Crack sealing, patching of concrete
- Bearing realignment
- Spot steel repairs or welds
- Deck joint repairs

3.4.4.4 *Module B4-Replacement*

Includes planned or reactive replacement of components at end-of-life, such as:

- Deck surface overlays or replacement of pavement surface
- Expansion joints

- Bearings or railings

3.4.4.5 *Module B5-Rehabilitation*

Covers major renovation or reconfiguration work that extends service life or updates functional requirements. Examples include:

- Bridge widening or seismic retrofitting
- Upgrading of safety barriers or drainage systems
- Full deck reconstruction

During the operation phase, regular maintenance activities, such as painting railings, sandblasting, use of de-icing salt, replacement of pavement surface, waterproofing, corrosion protection measures take place to ensure the bridge would perform its services safely without intervention. **Table 3-2** is a compilation of some common bridge maintenance and replacement activities.

Table 3-2: Common bridge maintenance activities[20]

Bridge element / equipment	Maintenance action
Steel girders	Includes Product and material sourcing[a]
	Complete renewal of corrosion protection
Concrete deck	Partial renewal of surface (minor repairs)
	Patching spalls and shallow potholes (minor repairs)
Concrete edge beam	Total replacement (major defects)
	Partial renewal (minor defects)
Expansion joints	Total replacement
	Minor repairs
	Cleaning
Bearings	Total replacement
	Painting exposed surfaces (minor repairs)
Road surface	Total replacement
	Minor repairs
Railings	Total replacement
	Minor repairs
Safety barrier	Total replacement

a - Raw material souring can trigger material extraction, processing, and production during the maintenance activities, these impacts should be estimated especially for bridge rehabilitation projects for example – rehabilitation of a steel girders.

[20] Gervásio, H., da Silva, L. S., Perdigão, V., Orcesi, A., & Andersen, R. (2015). Influence of maintenance strategies on the life cycle performance of composite highway bridges. Structural Engineering International, 25(2), 184-196. https://doi.org/10.2749/101686614X14043795569978

3.4.4.6 *Module B6-B7-Operational (Energy and Water)*

Module B6 is associated with the operational energy impacts such as street lighting and Module B7 can include operational water use for deck cleaning, washing of the bridge structure.

3.4.4.7 *Module B8-User*

User related environmental impacts come from traffic over the bridge during its life time. These impacts should be considered in cases when:

1) Traffic changes during construction will make trips longer. This can be included in A5 during initial construction
2) If maintenance or repairs require closing the bridge, trips will be longer. For example, choosing one repair method over another could affect this.
3) When a new bridge is part of a bigger transport route plan, not including User related environmental impacts could give misleading results. For example, comparing a highway route with a longer bridge but shorter overall route vs a shorter bridge with a longer route.
4) When comparing different transport mode types, such as light rail, highway and subway.

Calculation of user-related impacts requires an appropriate traffic model to evaluate journey lengths. Over time, user-related impacts—particularly carbon emissions—are expected to decrease as better transport options continue to develop. However, in the absence of an agreed-upon calculation method, careful consideration is required when assessing the impacts of this module.

3.4.5 End-of-Life (EoL) – Decommissioning or Demolition Phase (C1-C4)

At the end-of-life phase, the bridge is assumed to be demolished, and materials are sorted for recycling, reuse, or landfill disposal. Demolition involves dismantling or disassembling concrete, steel, asphalt, and other components, generating waste that must be appropriately managed. Concrete and asphalt materials (e.g., reclaimed asphalt pavement – RAP) may be crushed and reused or recycled depending on local practices and specifications. End-of-life scenarios should be defined based on project-specific assumptions, including material-specific recovery, reuse, recycling, or disposal pathways.

For steel-composite bridges, the components are typically recycled at high rates, depending on regional practices and project-specific conditions. Concrete and asphalt materials are typically crushed and either recycled or, if necessary, disposed of in landfills. Recycled hydraulic concrete are often processed to recycled concrete aggerate used on roadway subbase and base layers. Reclaimed asphalt overlay are processed as reclaimed asphalt pavement material use in new asphalt mixtures for roadway construction

The EoL phase therefore includes:

- Demolition activities (use of construction machinery, equipment, and road warning signage)
- Transportation and processing of materials
- Recycling, reuse, or disposal of components and materials

The EoL phase should consider the potential for designing bridge components for disassembly

and reuse, applying cradle-to-cradle concepts. Materials and components should be evaluated for recyclability, reusability, or recovery, while accounting for realistic diversion rates. Concrete, asphalt, structural/reinforcing steel, and other materials should be considered according to local recycling practices.

3.4.6 Beyond Life Cycle – Benefits and Loads (D)

Phase D encompass benefits and loads occurring beyond the defined system boundary of life cycle of the bridge, arising from reuse, recycling, or energy recovery of materials/products at end-of-life coming from reuse recycling and recovery of different products. These include avoided burdens from material substitution (e.g., recycled steel displacing primary steel production) or energy recovery displacing conventional energy generation, biogenic carbon, recycling benefits or loads beyond system boundary, credits or renewable energy generated on site. Carbon sequestration potential of landscape elements also falls under this module. Biogenic carbon refers to carbon stored and released over time depending on end-of-life fate. Accounting for biogenic carbon and sequestration should follow recognized standards (e.g., ISO 21930 or EN 15804 where applicable), ensuring consistency in system boundary and timing of emissions/removals.

Allocation refers to the partitioning of input or output flows of a process or product system between the system under study and other product systems.

Best practice guide for allocation-based ISO standards ISO 14044:2006 and ISO 21930:2017:

1. Avoid allocation where possible through subdivision
2. Apply cut-off approach for recycled materials by default
3. Use physical allocation (mass/energy) for multi-output processes
4. Use economic allocation only if physical not feasible
5. Require sensitivity analysis if allocation choice changes results >5%

When allocation cannot be avoided, input and output flows should be partitioned using physical relationships (e.g., mass, energy content) or economic value as a last resort using ISO 14044 Allocation Principles.

Allocation is particularly relevant in bridge LCA studies when dealing with materials that are:

- Derived from multi-product processes (e.g., steel, cement, asphalt and hydraulic cement concrete production).
- Recycled or reused from previous infrastructure projects.
- Co-products of other industries (e.g., fly ash from coal combustion, blast furnace slag from steel production).
- Construction and demolition waste

Key allocation principles from ISO 14044 require

- Inputs and outputs must be allocated using clearly documented and transparent

procedures.

- The sum of allocated inputs and outputs should match the total of the original system prior to allocation.
- When multiple allocation methods are valid, conducting a sensitivity analysis helps assess their impact on results.
- Unit processes requiring allocation must be explicitly identified and included within the defined system boundary.

Well-designed allocation rules prevent double counting of environmental credits and ensure that no significant factors are omitted. These rules should reflect actual physical or economic relationships between co-products and be documented in a clear, understandable manner for all stakeholders involved. **Appendix D** provides more details on Allocation methods with examples.

3.5 Selection of Impact Categories and Impact Category Indicators

Deciding on the impact categories and impact category indicators are steps that should also be taken in the Goal and Scope definition and are critical steps to ensure the accurate evaluation of a bridge environmental performance over its whole life cycle. To decide on the choice of impact categories and subsequently impact category indicators, the following criteria and parameters should be taken into consideration:

- The impact categories and indicators should be in line with the assessment study goal and scope. For example, if the focus of the study goal is on climate change evaluation, global warming potential (GWP) – CO2eq needs to be evaluated. Multi-indicator reporting is strongly encouraged. Single-indicator decision-making is discouraged due to trade-offs between impact categories.
- Availability of data is a critical factor. Those categories for which complete and accurate data collection and/or estimation can be carried out, should be considered for assessment. When data is limited or no data is available suitable assumptions should be made to assess relevant impacts and assess sensitivity of these inputs.
- To ensure consistency and comparability of methods and results, only established methodologies, such as IMPACT World+, ReCiPe, TRACI, ILCD should be applied in the assessment of impact categories and indicators. TRACI is one of the methods used in North America.
- Regional/geographical location of the asset (bridge) should be considered while selecting the impact categories and category indicators.

3.6 Defining the Interpretation Process

The interpretation phase is the final step in the LCA process. It involves analyzing the findings from the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) phases to ensure the results are consistent with the defined goal and scope of the LCA. This phase also identifies limitations, evaluates the significance of the results, and provides clear recommendations for decision-making. For bridge LCAs, the interpretation phase transforms the outputs from the LCIA process into actionable insights, enabling conclusions to be drawn, the significance of findings to

be understood, and targeted recommendations to be developed for LCA and sustainability experts, bridge engineers, clients, and decision-makers.

There are a number of considerations while defining the interpretation process:

(a) Alignment of the interpretation process with the goal and scope of the study should be ensured.

(b) Hotspot analysis and identification of major issues should be carried out to assess the contribution of life cycle modules, different materials (from the asset: bridge) and processes to analyzed impact categories and impact category indicators. This can be done using contribution analysis and/or sensitivity analysis exercise(s).

(c) Evaluation of the completeness and consistency of the modelling inputs, outputs, life cycle modules, impact assessment method(s), data sources as well as assumptions made with the defined study goal and scope should be carried out.

(d) Evaluation of sensitivity analysis results to determine robustness of conclusions and influence of key assumptions (e.g., allocation, service life, traffic modelling).Conclusions for the performance of each material, design choice, and life cycle modules, limitations of the study (data quality, variability and uncertainty factors in LCIA), and final recommendations (based on the study goal, scope and needs) should be provided at the end of the interpretation process.

Interpretation considerations shall be defined in the goal and scope phase and applied throughout the study, not only at the end.

3.7 Data Quality Requirement

All bridge LCA studies conducted under this guideline shall implement a Data Quality Assessment (DQA) framework to ensure transparency, consistency, and methodological robustness. Data quality requirements shall address technological, geographical, and temporal representativeness; completeness of inventory flows; consistency of system boundaries and allocation procedures; and documentation of assumptions.

The level of data quality applied shall be commensurate with the intended application of the study (e.g., screening-level planning assessment versus design-stage comparative LCA). Detailed procedures for Data Quality Assessment, including evaluation criteria, pedigree matrix application, and documentation requirements, are provided in Chapter 4.

4. Life Cycle Inventory

Life Cycle Inventory (LCI) is a critical step in the Life Cycle Assessment (LCA) process, defined by ISO 14040[21] as the "*phase of LCA involving the compilation and quantification of inputs and outputs for a product, system or service throughout its life cycle*." During this phase, data on the environmental impacts of a product or system are gathered, covering all stages from raw material extraction to disposal or recycling. Goal and scope established **Chapter 3** guides the data collection process, ensuring that all relevant unit processes within the system boundaries are covered. The LCI phase forms the foundation of the Life Cycle Impact Assessment (LCIA) phase by providing detailed data on resource usage, energy consumption, emissions, waste generation, and other environmental flows.

4.1 Inventory Data

LCI data can be classified into primary and secondary data.

Primary data is directly measured or collected from specific activities related to the studied system. For infrastructure projects, this may include project-specific information such as material quantities, equipment uses, fuel consumption, transportation distances, and construction activities. Because primary data reflect the specific conditions of the project under assessment, they are typically associated with processes in the foreground system, which includes activities directly controlled or specified within the study scope. The quality and completeness of primary data are important, as they strongly influence the accuracy and representativeness of the LCA results.

Secondary data, on the other hand, is sourced externally from databases (e.g., Ecoinvent, GaBi), literature, industry reports, or other previously developed datasets. These data are commonly used to represent processes that are outside the direct control of the project, such as material production, fuel production, electricity generation, or other upstream supply chain activities. Such processes are typically part of the background system.

Although secondary data are often used to represent background processes, the distinction between primary/secondary data and foreground/background systems is not strictly equivalent. In practice, foreground processes may sometimes rely on secondary data when project-specific measurements are unavailable, and background datasets may themselves be developed from aggregated primary data sources22.

Given the time and resource requirements associated with collecting project-specific data, it is not always feasible to obtain primary data for all processes in an LCA study. As a result, most infrastructure LCAs rely on a combination of primary data for key project activities and secondary data from established LCI databases to ensure completeness. When using secondary data, it is

---

[21] ISO (2006a). ISO 14040 International Standard. In: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organisation for Standardization, Geneva, Switzerland. ISO, 2006b. http://www.iso.org/iso/catalogue_detail?csnumber=37456

22 U.S. Environmental Protection Agency, Office of Chemical Safety and Pollution Prevention. (2024). *A vision and plan to improve secondary life cycle assessment data used in environmental product declarations*. U.S. Environmental Protection Agency.

important to evaluate its suitability for the study by considering factors such as system boundaries, geographic representativeness, technological relevance, and temporal coverage to ensure consistency with the study's goals and scope.

LCI data can also be classified into inputs, outputs, emissions and other environmental aspects according to ISO 14040.The goals of LCA study guides which categories need to be defined in more detail. **Table 4-1** provides the four categories and related sub-categories for a bridge infrastructure. A Data Quality Assessment (DQA) should be conducted to evaluate the representativeness, reliability, completeness, and consistency of all life cycle inventory data used in bridge LCA studies. Minimum primary data requirements and acceptable use of secondary data are defined in Sections 4.2.7 and 4.2.8.

4.2 Unit Processes

Before conducting the Life Cycle Inventory (LCI), the bridge system should be modelled as a network of interconnected unit processes. Each unit process modelling provides a structured representation of the infrastructure system and helps identify the data required for the inventory analysis.

A unit process is defined as the smallest element considered in a life cycle inventory analysis for which input and output data are quantified. Each unit process represents a specific activity within the product system and includes all relevant material and energy inputs as well as outputs such as products, co-products, emissions, and waste streams.

According to ISO-based LCA methodology, the overall product system is composed of multiple unit processes connected through product and energy flows, forming a process network that represents the full life cycle of the studied system.

In infrastructure LCAs, unit processes may represent activities such as:

- Raw material extraction (e.g., aggregate quarrying or iron ore mining)
- Material production (e.g., cement manufacturing, steel fabrication)
- Component manufacturing (e.g., precast concrete girders)
- Transportation of materials and components
- On-site construction activities
- Maintenance or rehabilitation processes

Each unit process contains defined input flows (e.g., materials, fuels, electricity) and output flows (e.g., intermediate products, emissions to air, water, or soil). These flows connect processes together to form the overall system model.

Example of Unit Processes in a Bridge System

For a bridge structure, the LCA system model may include several interconnected unit processes such as:

- Cement production
- Aggregate extraction and processing

Table 4-1: Inventory data categories

Category	Sub-Category	Description	Example
Inputs	Energy	Energy consumed during the bridge's construction, use, and demolition phases, including all forms of energy	Electricity for lighting or machinery, diesel fuel for construction vehicles, natural gas for heating or equipment operations
	Raw Materials	Raw materials needed for the production and construction of the bridge include mined or harvested resources	Concrete (cement, sand, aggregates), steel (iron ore, scrap), timber, aggregates (gravel, sand), and bitumen
	Ancillaries	Inputs used during the life cycle that support but are not directly part of the bridge structure	Lubricants for machinery, reinforcing steel coatings, formwork materials (wood, plastic), water for cement mixing, and concrete additives
	Other Physical Inputs	Other non-material or physical inputs required for the construction, use, or maintenance of the bridge	Water for cleaning, tools, machinery, spare parts, or scaffolding used during construction
Outputs	Products	The final product or primary output of the bridge construction process, typically the bridge structure itself	Concrete bridge deck, steel beams, guardrails, and any components that make up the completed structure
	Co-products	Secondary products or by-products created during the life cycle but not the primary product. These can have commercial value or be recycled	Slag, cement kiln dust (CKD) used as filler, or scrap timber that can be repurposed
	Waste	Materials discarded or that end up as waste during any phase of the bridge’s life cycle, including construction, use, and demolition	Construction debris, scrap metal, excess concrete, waste packaging, or soil contamination
Emissions	Emissions to Air	Pollutants released into the air during the life cycle stages of the bridge, including gases and particulates	CO2 emissions from cement production, Criteria Air Pollutants (e.g., NOx, SOx, PM) and particulate emissions

			from diesel machinery, volatile organic compounds (VOCs) from paints or coatings
	Emissions to Water	Pollutants released into water bodies, which can include chemicals, sediment, or runoff	Oil spills, chemical runoff from construction, stormwater runoff containing cement particles, wastewater from concrete mixing
	Emissions to Soil	Pollutants or contaminants that affect soil quality, often resulting from improper disposal or leakage of materials	Heavy metal contamination from paint or coatings, oil leaks from machinery, or hazardous waste from demolition
Other Environmental Aspects	Noise	Environmental noise produced during bridge construction, maintenance, or demolition, which may impact local communities or wildlife	Noise from construction equipment (e.g., jackhammers, cranes), traffic noise during bridge maintenance, or piling operations
	Radiation	Exposure to ionizing radiation or electromagnetic fields (EMF) associated with certain bridge materials or construction activities	Radiation from materials such as certain types of concrete or steel, or from equipment emitting EMF
	Land Use	Impacts on land use due to the construction of the bridge, including soil compaction, vegetation removal, or changes in land use patterns	Land clearing for the bridge footprint, road access, and construction staging areas
	Other	Any other environmental impacts that don't fall into the above categories but still need to be tracked for sustainability or impact assessment	Impact of construction on wildlife, visual impacts, or changes in local ecosystems

Note: This table presents example categories of inventory flows and environmental aspects that may be considered when compiling life cycle inventory (LCI) data for bridge infrastructure. It is intended as a conceptual guide to support systematic identification of relevant inputs, outputs, emissions, and other environmental considerations across life cycle stages. The examples are illustrative and not exhaustive; practitioners should adapt them to the project scope, system boundaries, and data availability.

- Concrete batching and mixing
- Reinforcing steel production
- Girder fabrication
- Transportation of materials to site
- Bridge deck construction
- Equipment operation during construction

These unit processes collectively form the bridge construction system, where outputs from one process become inputs to another. For example, cement and aggregates feed into the concrete production process, which then feeds into bridge deck construction.

Developing a system model that clearly defines unit processes and their relationships is critical because it determines the data requirements for the inventory analysis. Once the system model is established, data collection can be organized around each identified unit process.

ISO 14044 recommends documenting the system model using a process flow diagram showing unit processes and their interrelationships, including where each process begins, the operations that occur within it, and where its outputs are transferred to other processes.

Figures 4.2 and 4.3 in this guideline illustrate examples of such system models for cement and steel production. A similar modelling approach should be applied when representing bridge systems, where the infrastructure asset is represented as a network of unit processes spanning material production, transportation, and construction stages.

4.3 LCI Workflow and Key Procedures

The LCI procedure involves several key steps carried out iteratively to ensure that data collection and modelling meet the study's objectives. Steps involved in attaining a comprehensive LCI can be categorized into two main groups: data collection and data analysis categories (**Figure 4-1**).

Data collection is a critical and resource-intensive component of the bridge LCA. It involves development of data collection plan and systematic collection and quantification of input and output flows defined by goal and scope of the study.

Data analysis ensures the accuracy and reliability of the LCI results. Data analysis begins with data processing and validation, where collected data is cleaned, preprocessed, and cross-verified with multiple sources to ensure consistency and correctness. Handling data gaps and uncertainties is a common challenge, requiring practical approaches to address missing data, such as sensitivity analysis. System modelling follows, translating the data into meaningful insights by mapping it to unit processes and functional units. This step involves the allocation of flows and releases, which is essential for ensuring that environmental impacts are correctly attributed to each stage of the system. Throughout the analysis, decision rules and the continuous refining of system boundaries are applied to enhance the study's accuracy and ensure it reflects the real-world context of the bridge project under assessment. LCI generation is an iterative process, meaning that new requirements or limitations may arise as data is collected and analyzed, leading to changes in data collection procedures or even re-evaluation of LCA study’s goal and scope.

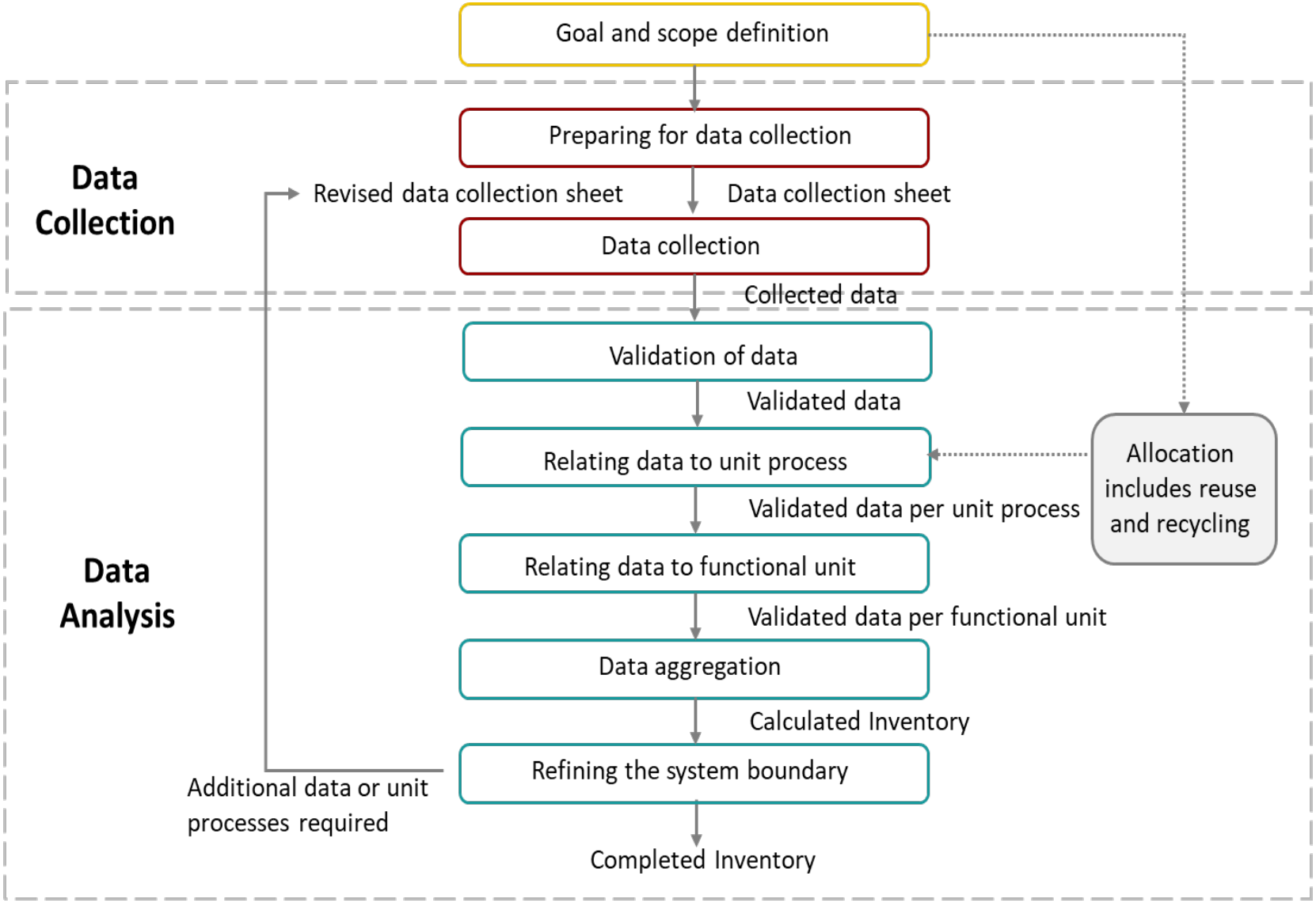


Figure 4-1: The LCI analysis required by ISO 14044 for conformant LCAs.

4.3.1 Preparing for Data Collection

ISO 14044[23] outlines preparation of comprehensive data collection plan as first step for Life Cycle Inventory (LCI). This plan defines the procedures for gathering the necessary data, ensuring consistency with the study's goals. The types of data (primary or secondary) and their quality requirements must be established during the scoping phase. A key aspect of the data collection plan is determining the representativeness of the data. This includes considering its relevance based on regional, temporal, and technological factors and ensuring the data applies to the LCA application. The distinction between primary and secondary data should be made after conducting a review of the available data. This plan may need to be readjusted during the data collection process as new information becomes available.

For example, in a bridge project involving material production, transportation, and placement of a bridge deck (**Table 4-2**), the data collection plan would identify which processes will use primary data and which may require secondary data. Primary data, collected directly from specific processes, is always preferred for its accuracy. However, in cases where primary data is not available, secondary data can be used. This secondary data, although helpful, should be carefully reviewed and adjusted to reflect the local conditions of the project. For instance, the electricity used during material production or transportation may need to be adjusted based on the local energy grid mix. It's important to use the same secondary data format – e.g. if Ecoinvent database are used for analysis the industrial reports should be converted to an Ecoinvent data format for consistency. Same secondary database should be used where possible.

Table 4-2: Example of data collection planning

Stage	Product	Process	Primary Data	Secondary Data
Material Production	**Concrete**	Production of concrete (mixing, batching)	Direct measurement of materials, energy, and emissions from concrete production	Industry databases (e.g., Ecoinvent, GaBi) for average production data
	Steel	Steel production (manufacturing, processing)	Energy use, emissions from steel mills	Industry reports, regional steel production data
	Timber	Wood component production (extraction, manufacturing, processing)	Energy use, emissions from Timber mills	Industry reports, regional wood production data

[23] ISO (2006b) ISO 14044 International Standard. In: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland. http://www.iso.org/iso/catalogue_detail?csnumber=38498

Construction	**Concrete**	Transportation and placement of concrete	On-site data for transport distance, fuel consumption, and energy use during placement	Construction industry reports, transportation databases
	Steel	Steel transportation and installation	Data from equipment usage, emissions from transport, and installation activities	Secondary data from similar bridge projects or generic databases
	Timber	Wood component transportation and installation	Data from equipment usage, emissions from transport, and installation activities	Secondary data from similar bridge projects or generic databases

The Data Management Plan (DMP) should be developed during the planning stage of the LCA study and describe the procedures for collecting, organizing, documenting, and maintaining inventory data throughout the project. The DMP should outline processes for data collection, inventory reporting, data updates, and internal quality control procedures to ensure consistency and transparency in the study.

The data collection plan within the DMP should also specify the input and output flows associated with each unit process, including materials, energy, emissions, and waste flows relevant to the system being studied. These flows should be selected in accordance with the impact assessment method defined in the goal and scope phase, as the chosen impact categories determine which inventory flows are required.

For example, if the study focuses solely on global warming potential (GWP), the emissions inventory may be limited to greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O. In this case, other emissions data not relevant to the selected impact category, such as particulate matter ($PM_{2.5}$), may be excluded from detailed tracking.

4.3.2 Data Collection

Data collection is crucial to identify and quantify relevant flows within the process to model a unit process for a Bridge LCA. To ensure the most complete and accurate inventory, data should be collected from multiple sources. Some key sources for data collection are process designers, project drawings and documents, engineering calculations, design standards and regulations, government and industry reports, existing literature, estimations from similar operations and comparable unit processes in established databases.

According to ISO 14044 Section 4.3.2, the data collection should ensure consistency and transparency. the following actions should be used to ensure the requirements are met:

1. *Process Flow Diagrams:* These diagrams are key in visualizing the system's operations.

They show all unit processes and their interrelationships, helping to clarify the flow of materials, energy, and emissions across the system. This visualization is crucial in understanding the system's operations and identifying potential areas for improvement.

2. *Data Collection Forms and Templates:* Prepare standardized forms and templates to streamline the collection process.
3. *Unit Process Descriptions:* Provide detailed descriptions of each unit process, including the factors influencing inputs and outputs.
4. *Identification of Relevant Flows:* List the flows and relevant data for each unit process based on operating conditions.
5. *Unit Flow Listings:* Document the units of measurement for each flow, ensuring consistency across the inventory.
6. *Data Type Identification:* Following the scoping phase guidance, define the data type needed for each process.
7. *Calculation Techniques:* Describe the methods for collecting and calculating data to ensure accuracy and consistency.
8. *Special Cases or Irregularities:* Document any unique circumstances or data irregularities that might affect the analysis.

4.3.2.1 *Type of Processes*

Bridge LCA processes are categorized into upstream, downstream, and processes under the control of the initiating party. Depending upon the goal and scope a number of upstream and downstream processes need to be considered for complete process flow diagrams. Upstream and downstream processes for bridge infrastructure are defined by their position relative to bridge construction and use. Upstream processes typically cover raw material extraction and production, whereas downstream processes encompass construction, maintenance, service life, and end-of-life stages. Secondary data is generally appropriate for upstream and downstream processes where primary data collection may be impractical.

Figure 4-2 shows an example of a process diagram that outlines the different processes involved in manufacturer of steel products such as steel frames. Steel production requires various energy inputs, including electricity, coal, and natural gas. Each energy source has unique upstream environmental impacts or declarations intricately linked to the production of that energy resource. For instance, the electricity used in steel production could be sourced from coal, natural gas, or renewable energy, each with distinct environmental impacts. Hence, several upstream unit processes must be considered and modelled to determine the total energy consumption and emissions from the production of 1 tonne of steel frame components. Should the need arise, the study demands additional modelling of upstream processes to meet the system boundaries defined in the goal and scope of the LCA study.

4.3.2.2 *Data Collection Methods*

Table 4-3 provides an overview of recommended data-collection methods for different life cycle phases of bridge. The method used for data collection depends upon the goal of the LCA study.

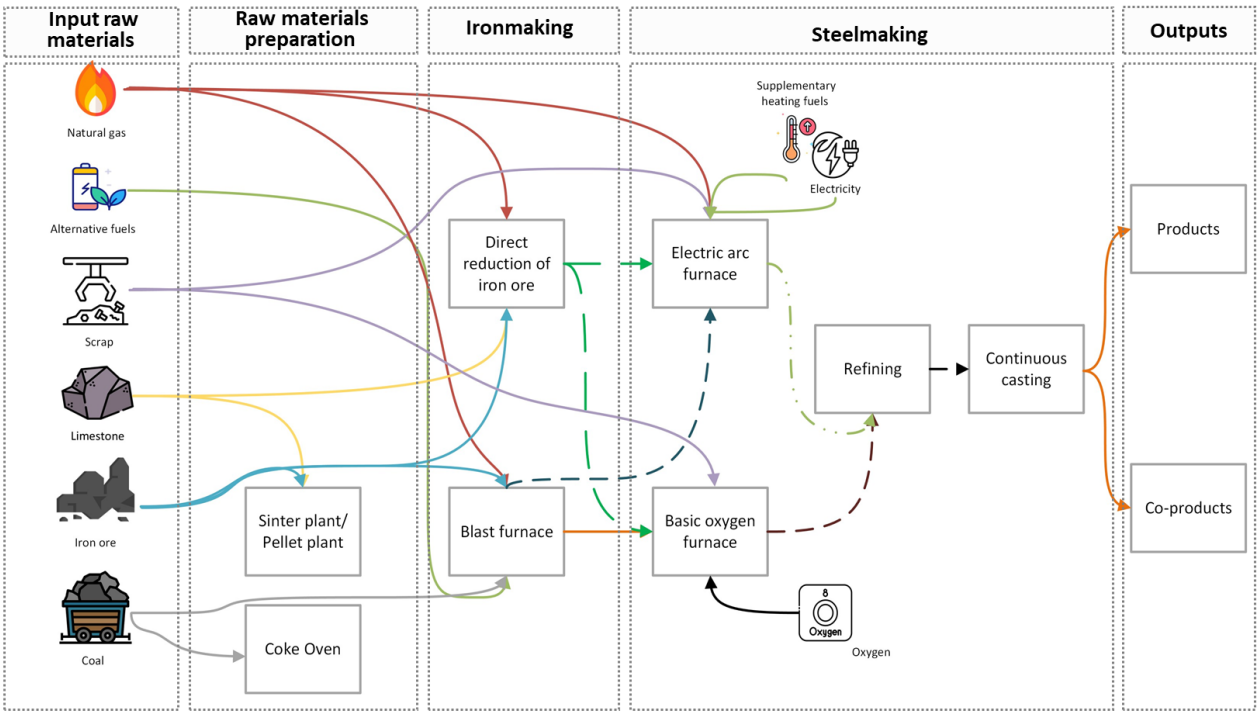


Figure 4-2: Steel production flow chart[24]

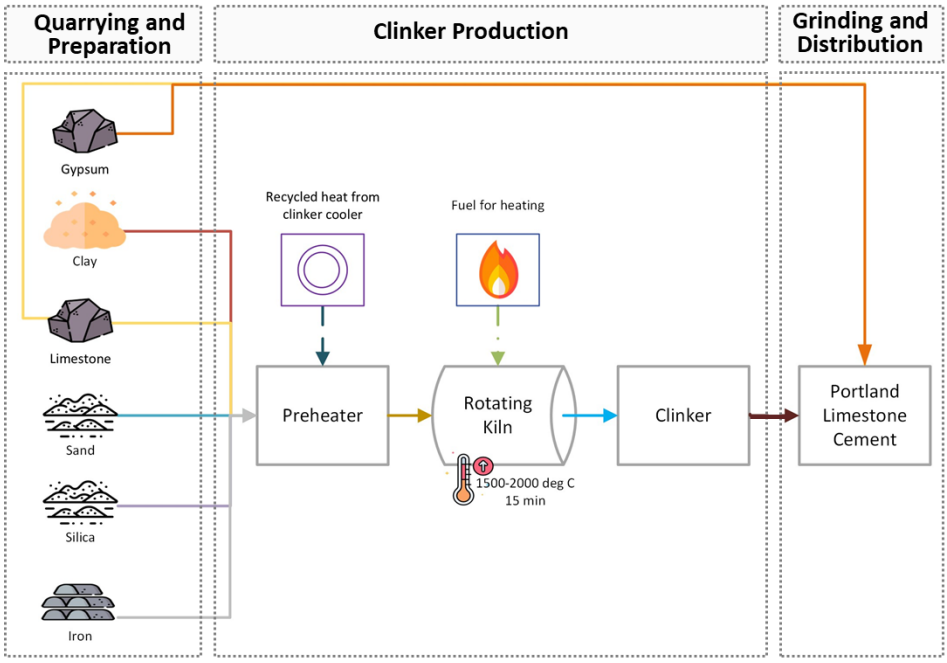


Figure 4-3: Cement production flow chart[25]

[24] Worldsteel Association. The steel making process. https://worldsteel.org/wp-content/uploads/steelmaking-process.pdf
[25] Cement Association of Canada. (2021). How cement and concrete are made. https://cement.ca/the-cement-and-concrete-industry/how-cement-and-concrete-are-made/

For instance, during the construction phase, primary data may be obtained from bridge contractors, including equipment fuel consumption, construction schedules, and site energy use, while secondary data are typically used for upstream processes such as material production. Conversely, if the LCA focuses on long-term durability and structural performance, primary data for the use phase may be prioritized, with upstream and downstream processes relying on secondary data. Potential applications and process categorizations are further discussed in later sections of this chapter (Section 3.3). In a bridge project, it is possible that the LCI data is collected by using some or all the methods listed in **Table 3-3**. This is because the LCI databases are still developing, and it is not possible to have a single source capable of providing all the required data.

Table 4-3:Data collection methods

Method	Description	Data Type	Considerations
Direct Measured Emissions	Source-specific primary data obtained through direct emissions measurements.	Primary	Most reliable and representative but also the most expensive and resource intensive.
Process-Activity Data and Modeling with Emission Factors	Collection of activity data (e.g., energy use, material consumption) and conversion using emission factors.	Primary or Secondary	Use of Primary data (site-specific) is more reliable than Secondary (national averages).
Financial Activity Data and Modeling with Emission Factors	Estimation of emissions based on financial records and EIO-LCA database.	Secondary	Approximate results best used when process-activity data are unavailable.
Direct Literature Data	Use of publicly available literature or database data as proxies.	Secondary	Must ensure representativeness and document sources transparently.

During the data collection process any discrepancies between sources must be identified and justified, and missing flows should be addressed through balance checks. Each flow must be clearly defined and consistent with other dataset flows. Raw data forms the basis for deriving flow values and should be well-documented to allow for easy updates and customization in future projects.

4.3.3 Validation of Data

A validation check must be conducted on all data collected in the context of Bridge LCA. This check ensures that the data satisfies the data quality requirements as outlined in the goal and

scope of the study (refer to **Chapter 3**). The validation process ensures that all inventory inputs and outputs are adhering to mass and energy balance principles. Mass balance is an important principle in Life Cycle Inventory (LCI) modelling used to ensure that all material inputs and outputs within a unit process are properly accounted for. In accordance with conservation of mass, the total mass of inputs entering a process should equal the total mass of outputs leaving the process, including products, co-products, emissions, and waste streams. This involves performing a mass balance and energy balance check to verify that the inflows and outflows of the system align. For instance, for a unit process related to bridge construction, such as the transportation and fabrication of a steel girder for the bridge's superstructure, the mass balance check would require that the mass of inputs (e.g., energy related to transportation, surface preparation, materials used for welding, type of studs) matches the mass of outputs (e.g., final girder, wastes).

Other Key Considerations for Validation

- *Planning Level:* Ensure that the data aligns with the overall planning level of the LCA.
- Design Level: Validate data based on the project's design specifications and intended outcomes.
- *Complexity Level:* Ensure that the complexity of the unit process is appropriately reflected in the data.
- *Level of Detail of Data (Data Granularity):* Confirm that the data granularity meets the study's requirements.
- *System representation:* Verify that the network of processes accurately represents the entire life cycle of the bridge, including the relevant upstream and downstream processes.

Additionally, while not mandatory, a beneficial step in the validation process is to compare the results with those from similar studies. This can help identify discrepancies and improve the reliability of the data. Any comparison should consider the definitions and boundaries of the unit processes being compared. By following these steps, the integrity and reliability of the data can be ensured, supporting the robustness of the Bridge LCA results.

4.3.4 Relating Data to Unit Process and Functional Unit

The quantitative input and output data for unit processes must be calculated in relation to the reference flows. Based on the flow chart and the relationships between unit processes, all flows are ultimately linked to the functional unit. Inventory data collected for unit processes must be aggregated to compute overall inputs and outputs aligned with the functional unit defined in the goal and scope phase. This process should be applied to each life cycle stage, with tailored procedures ensuring accuracy. Reference flows for material production and subsequent life cycle stages such as maintenance, rehabilitation, and use should be clearly established. Since unit processes contribute to fulfilling the function of the bridge, their quantitative data must be appropriately aligned with the reference flow. Additionally, data collected from some life cycle

phases (e.g., construction activities) often represent the entire project and must be translated to the functional unit when necessary.

4.3.5 Data Aggregation

Data aggregation involves compiling upstream information, summing it, and presenting it as a single value. Aggregated inventory results should be reported in terms of the chosen functional unit, ensuring consistency across different life cycle stages. However, aggregation is only valid when flows or environmental impacts correspond to equivalent substances, are calculated using the same methodology, and maintain consistent units.

Major steps involved in data aggregation if unit processes are:

1. Identification of unit processes contributing to a process based on system boundary
2. Evaluation of proportions contributed by different unit processes to the aggregated process.
3. Aggregation of unit processes based on proportions to identify aggregated inputs and outputs
4. Storage of aggregated for further analysis and reporting of LCA results

For example, the functional unit could be defined as “a bridge designed for a service life of 75 years, for a maximum hourly traffic of 1000 vehicles”[26]. It is essential that consistent units are used for reference flows. **Figure 4-4** shows an example of LCA conducted for the deck of Bayfield River Bridge[27]. Bayfield River Bridge is a steel box girder bridge made of ASR steel with a single span of 40 m and a 200 mm thick reinforced concrete (30 MPa) deck located in south of Clinton, Ontario. Hence, 120 m^3 (288,000 kg) of reinforced concrete (considering 2400 kg/m3 density) is required for bridge deck. Assuming one cubic meter of reinforced concrete contains 0.125 m^3 (300 kg) of cement and 120 kg of steel, reference flows in bridge deck of 120 m^3 can be estimated. Hence, the inventory input-output flows for this bridge deck can be expressed in terms of reference flow 36,000 kg of cement, and 14,400 kg of steel reinforcement. Where the inventory database is structured per unit mass or production volume, data can be translated to the functional unit during aggregation. Maintaining inventory databases in mass- or volume-based formats ensures alignment with commercial and literature data sources, facilitating consistency in LCA.

[26] Eriksen, J., Gervasio, H., Rebelo, C., Silva, L. S. D., Veljkovic, M., & Vesikari, E. (2008). Guidelines to perform life cycle analysis of bridges. In COST Action C25 Seminar on Sustainability of Constructions-Integrated approach to life-time structural engineering: 06/10/2008-07/10/2008 (pp. 5-27).

[27] Jalaei, F., Zhang, J., Mcneil-Ayuk, N., & McLeod, C. (2025). Environmental Life Cycle Assessment (LCA) for design of climate-resilient bridges–a comprehensive review and a case study. International Journal of Construction Management, 25(1), 99-114. https://doi.org/10.1080/15623599.2024.2304479

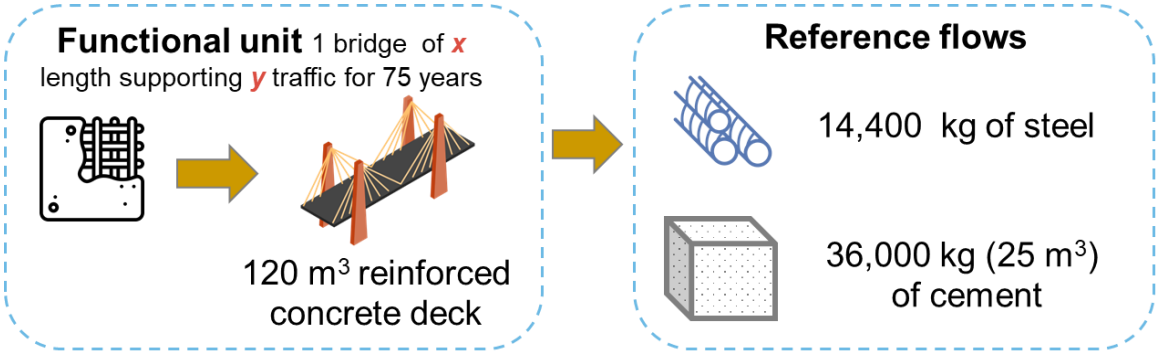


Figure 4-4: Example reference flows of steel and cement used for a steel bridge with reinforced concrete deck[28]

4.3.6 Refining the System Boundary

The system boundaries for a Bridge LCA define which material inputs, outputs, and processes are included in the inventory analysis. These boundaries are finalized after applying decision rules to the initial data set. Cut-off criteria are used to eliminate minor inputs and outputs with negligible contributions in terms of mass, energy consumption, or environmental impact. This approach optimizes the efficiency of the LCA by focusing resources on significant contributors while maintaining methodological rigor. The selection and application of cut-off criteria should align with ISO 14044:2006 and ISO 21930:2017[29].

For the purposes of this guideline, a flow may be considered insignificant when its contribution to the total environmental impact of the system is less than 1% for the relevant impact category. Conversely, flows that contribute greater than 1% of the total impact should be considered significant and included within the system boundary where feasible. This threshold helps ensure that decisions regarding system boundary exclusions are based on quantifiable criteria rather than solely on professional judgment.

However, exclusions should be applied cautiously. Even when a flow represents a small fraction of the total mass or energy input, it should remain within the system boundaries if preliminary analysis indicates that it may contribute disproportionately to environmental impacts (e.g., due to energy-intensive production processes or high emission factors).

Decision rules can be applied through the following steps to refine system boundaries:

- Identify relevant unit processes and life cycle stages where decision rules will be applied, such as concrete mixing, steel fabrication, or timber treatment.
- Address data gaps by using secondary data sources, literature values, or best estimates in

[28] Jalaei, F., Zhang, J., Mcneil-Ayuk, N., & McLeod, C. (2025). Environmental Life Cycle Assessment (LCA) for design of climate-resilient bridges–a comprehensive review and a case study. International Journal of Construction Management, 25(1), 99-114. https://doi.org/10.1080/15623599.2024.2304479

[29] International Organization for Standardization. (2017). ISO 21930:2017 Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services. ISO.

a conservative manner.

- Apply cut-off criteria to filter out minor material flows based on mass, energy consumption, or environmental significance.
- Perform sensitivity analyses to ensure excluded inputs and outputs do not significantly alter the overall results.
- Determine final material inclusions and exclusions based on agreed-upon cut-off thresholds during the scoping phase.
- Reassess and refine system boundaries iteratively, revisiting previous steps when necessary.

Cut-off criteria should be well-documented, as refining system boundaries is an iterative process. Sensitivity analysis is crucial in this refinement, enabling the evaluation of the effects of including or excluding certain unit processes, life cycle stages, or specific material inputs and outputs. Adjustments to system boundaries may be required if:

- Primary data collection for certain flows proves impractical, necessitating alternative data sources.
- Secondary data is unavailable or insufficient for specific materials or processes.

Certain unit processes are determined to be insignificant based on mass, energy, or environmental impact criteria.

For example, consider a bridge deck made of high-performance concrete. A chemical admixture may constitute less than 1% of the mix by mass, seemingly falling below a typical cut-off criterion. However, an initial analysis might reveal that this admixture significantly influences the environmental impact due to high-energy production or emissions. In such cases, the input should remain within the system boundaries despite its low mass contribution. This principle applies broadly to infrastructure materials, where even small quantities of certain chemicals or components can have substantial environmental or energy-related effects.

4.3.7 Data Quality Assessment (DQA)

A Data Quality Assessment (DQA) shall be conducted to evaluate the representativeness, reliability, and completeness of life cycle inventory (LCI) data used in bridge LCA studies. DQA ensures methodological consistency and defensibility for infrastructure-scale LCA.

Most common method of evaluating data quality is through utilization of Pedigree matrix. The pedigree matrix was inspired by Numeral Unit Spread Assessment Pedigree (NUSAP) and is used to transfer qualitive uncertainties into quantitative uncertainties[30]. The input data is scored across a range of parameters that depend upon the type of pedigree matrix selected. Most LCA tools adopt the five-parameter pedigree matrix that ranks data based on reliability, completeness, temporal correlation, geographical correlation, and technological correlation.

[30] Qin, Y., Cucurachi, S., & Suh, S. (2020). Perceived uncertainties of characterization in LCA: a survey. *The International Journal of Life Cycle Assessment*, *25*, 1846-1858. https://doi.org/10.1007/s11367-020-01787-9

Figure 5-4 provides a view pedigree matrix present in OpenLCA tool. The data scores are aggregated into related uncertainty factors that are used for determining standard deviations and probability distribution of data. Monte Carlo Simulations are than used to assess distribution of results.

	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimates (e.g. by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered ,over and adequate period to even out normal fluctuations	Representative data from > 50% all sites relevant for the market considered ,over and adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or >50% of the sites but from shorter time periods	Representative data from only one site relevant for the market considered or some sites but from shorter time periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal Correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of the data unknown or more than 15 years of difference to the time period of the data set
Geographical Correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area
Further technological correlation	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Figure 4-5: Data quality scores in pedigree matrix[31]

Uncertainty and Sensitivity analysis needs to be performed to identify influential parameters, prioritizing data collection, understand complex systems such as bridges, test robustness of final results and ensure transparent reporting. These form part of the last phase, Interpretation of an LCA study. Please refer to **Chapter 7** for more details on uncertainty and sensitivity related with

[31] GreenDelta. Data quality - openLCA 2 manual. https://greendelta.github.io/openLCA2-manual/advanced_top/data_quality.html

a Bridge LCA. Use of a pedigree matrix and Monte Carlo simulation is recommended for detailed design or comparative studies but may not be required for screening-level assessments.

4.3.7.1 Data Quality Indicators

In line with the ISO standards, each primary and secondary dataset used in a Bridge LCA study should be evaluated against the following indicators:

- Technological Representativeness

  The extent to which the dataset reflects the actual materials, construction methods, and technologies used in the project.

- Geographical Representativeness

  Alignment between the dataset and the geographic context of the project (e.g., Canada, province, regional grid mix).

- Temporal Representativeness

  Alignment between the dataset year and the project timeframe. Data less than 10 years old shall be preferred.

- Completeness

  Inclusion of all relevant material, energy, and emission flows within the defined system boundary.

- Consistency

  Harmonization of system boundaries, allocation procedures, and functional unit alignment across datasets.

- Precision and Uncertainty

  Degree of variability, assumptions, or estimated values within the dataset.

4.3.7.2 Acceptability Criteria and Documentation

The following criteria should be used for access dataset quality:

- Canadian or North American datasets shall be prioritized.
- International datasets may be used only where regional data are unavailable and must be justified.
- Datasets older than 10 years should be updated or justified.
- Allocation procedures must be documented and consistent across datasets.
- Any dataset materially influencing results (>10% of total GWP) must meet minimum technological and geographic representativeness.

For each dataset, the following shall be reported:

- Data source and reference

- Year of data
- Geographic scope
- System boundary
- Allocation method (if applicable)
- Modifications or adjustments applied
- Identified limitations

4.4 Documentation of LCI

Comprehensive documentation is essential to ensure transparency, consistency, and reproducibility of Life Cycle Inventory (LCI) results. All data inputs, modeling assumptions, sources, and methodological decisions must be clearly recorded and traceable.

The following aspects of LCI shall be documented:

- *Data Sources:* Specify the origin of all primary and secondary data (e.g., site-specific measurements, industry reports, environmental product declarations, national databases).
- *Assumptions:* Clearly state any assumptions made regarding service lives, maintenance intervals, recovery rates, default material properties, or operational conditions.
- *Allocation Methods:* Describe the approach used for allocating impacts (e.g., mass, economic, or energy-based) when multiple outputs or functions exist.
- *Temporal, Geographical, and Technological Representativeness*: Indicate the relevance of data in terms of time frame, region, and technology used.
- *Data Quality Assessment:* Summarize the completeness, consistency, and reliability of the data, and identify any significant data gaps or uncertainties.
- *Event-Based Modeling:* Explain how recurring events (e.g., repainting, component replacement) are translated into average annualized flows over the Reference Service Life (RSL).
- *Structured Format:* All documentation should be organized in a structured format (e.g., spreadsheet or LCI report annex) to facilitate review, third-party verification, or future updates.

4.5 Potential Pitfalls and Sources of Error

Mistakes in life cycle inventory can be avoided by taking into consideration the potential pitfalls and possible sources of errors.

Some key factors that need to be avoided in LCI procedure are:

- *Incomplete Data Collection:* Missing data or excluding certain life cycle stages (such as maintenance or end-of-life disposal) can lead to skewed results that fail to reflect the true environmental impact.

- *Data Quality Issues:* Inaccurate or outdated data may lead to poor conclusions. It's important to ensure that data sources are reliable and represent real-world conditions.
- *Overly Complex Modeling*: Model complexity should match the impact of each component or process. Focus on the major contributors and avoid over-detailing minor ones to keep the analysis clear and reliable..
- *Failure to Account for Regional Differences*: Some environmental impacts can vary depending on geographical location, such as energy generation mix or material availability. These differences should be considered when conducting an LCI.
- *Ignoring Uncertainty*: Not accounting for uncertainties in data, such as uncertainty arising from measurement errors, limited sample sizes, old data, non-regional data and others, can mislead decision-making. Sensitivity analysis is often necessary to identify how variations in data might affect the results.
- *Lack of Stakeholder Involvement*: Bridging the gap between engineering, environmental science, and decision-making requires collaboration. Inadequate involvement of all relevant stakeholders in defining goals and interpreting results can limit the effectiveness of the LCI study.

5. Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) translates life cycle inventory data into indicators that reflect potential environmental impacts. The purpose of LCIA is, "*understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product*". In this phase life cycle inventory results are translated into quantitative metrics, called impact indicators, that reflect potential environmental impacts of the process or product system. These indicators relate to natural systems, human health, and resource use and come from all input and output flows in the system.

Impact assessment is caried out in a series of three mandatory steps followed by optional steps:

1. Selection of impact categories, indicators, and models
2. Classification – assigning LCI results to impact categories
3. Characterization – calculating indicator results using characterization factors
4. Optional steps
    - Normalization–contextualizing results against a reference (e.g., per capita emissions)
    - Grouping – organizing impact categories by priority or type
    - Weighting–applying value-based preferences to indicators (not typically recommended in comparative assertions)

5.1 Mandatory Steps: Selecting Impact Categories, Classifying Indicators and Characterization Models

Impact categories represent specific environmental concerns to which the LCI results are assigned. These categories may be linked to resource use, energy consumption (inputs), pollutant emissions, and waste generation (outputs). The selected impact categories should be relevant to bridge infrastructure, such as global warming, acidification, eutrophication, ozone depletion, and resource depletion.

Each impact category is associated with a ***category indicator***—a quantifiable measure expressing the potential impact's magnitude. These indicators can occur at various levels in the cause-effect chain: midpoint indicators represent impacts closer to the emissions (e.g., GWP for climate change), while endpoint indicators reflect aggregated consequences on areas of protection like human health or ecosystem quality.

Characterization models define how emissions or resource used contribute to specific environmental impacts. These models yield characterization factors, which convert LCI results into comparable indicator results. For example, greenhouse gases such as CO2 and CO have varying global warming potentials (GWPs) over a specific time horizon, and the associated characterization models provide the factors needed to express them in a standard unit (e.g., CO_2-equivalents). ***Equation 5.1*** provides the principle of characterisation

$$Impact\ Category\ Result = \sum_i Amount\ of\ Substance_i\ X\ Characterisation\ Factor_i$$

Equation 5.1

In the LCIA phase, two main approaches are often used: midpoint and endpoint. Mid-point approach relies primarily on scientific information with lower uncertainty and subjectivity role in results. End-point approach on the other hand presents information in more understandable form and easier to communicate. However, the degree of uncertainty involved in end-point impacts is higher than mid-points. The end-point approach includes an additional step where mid-point impact categories are grouped and classified into endpoint areas, representing direct environmental and human impacts. End-point impact approach is not present for all developed impact assessment methods. For instance, TRACI 2.1 method only provides mid-point categories while ReCiPe provides both mid-point and end-point impacts. **Figure 5-1** shows ReCiPe mid-point approach used to convert amount of substance onto indicator. The inventory emissions can come from one or more sources and result in multiple environmental impacts. For example, the main sources of NOx for bridge come from transport and tailpipe emissions on jobsite equipment.

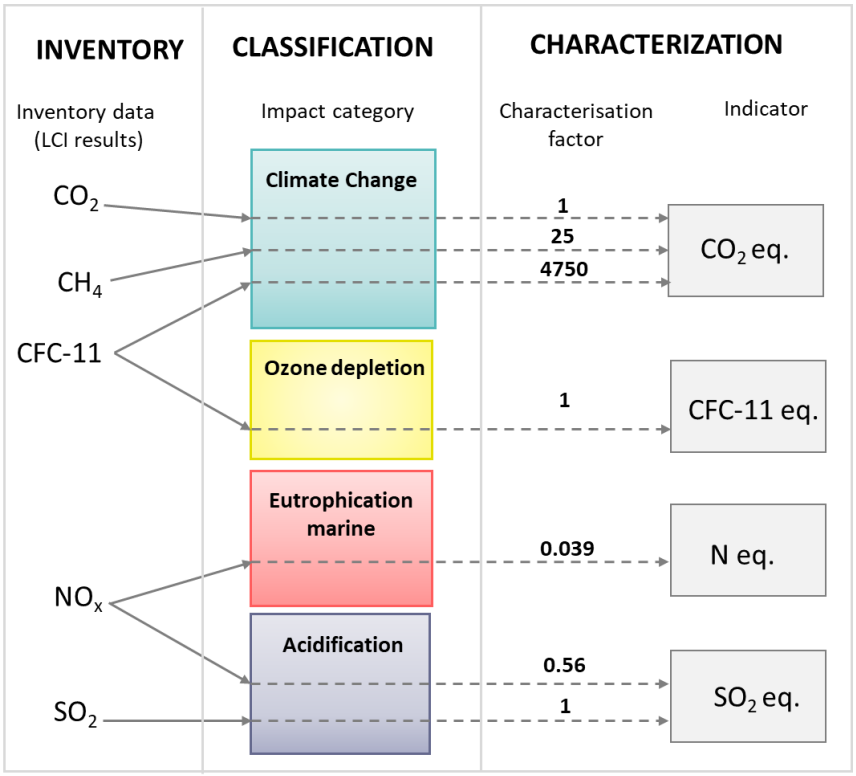


Figure 5-1:Classification and Characterization in ReCiPe mid-points[32]

Figure 5-2 shows process of attaining mid-point and end-point impacts for a bridge with steel reinforcements. Inventory results provide the number of emissions while the impact results are found using GWP characterization model where each gas is converted to CO_2-eq. (GWP). The end point impact climate change is attained by using end-point characterization model.

[32] Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., & Zelm, R. v. (2009). ReCiPe 2008-A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Holland

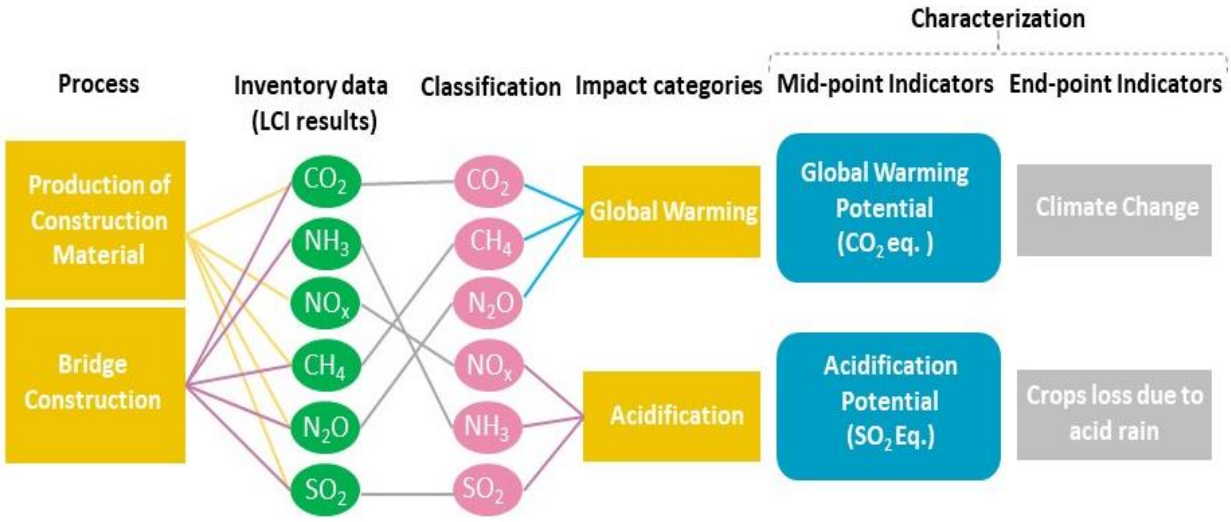


Figure 5-2: An example of process of attaining mid-point impact (GWP) and end-point Impact (Climate change) for a bridge

All data sources used for impact categories, indicators, and models must be clearly referenced. For greenhouse gas (GHG) emissions, characterization factors for CO_2, CH_4, N_2O, and other relevant gases are based on the IPCC Assessment Report 6[33] global warming potentials, unless otherwise stated. This ensures consistency with current international guidance for climate impact assessment. If new models or categories are introduced, their development must be justified with transparent rationale and citations. The goal and scope of the study guide the selection of relevant impact categories and indicators, ensuring alignment with the decision context of the bridge LCA.

5.2 Optional Elements

Optional elements, normalization, grouping and weighting, can be added in the LCIA to help in the results interpretation. However, when included they must be explicitly documented in the goal and scope of the study to ensure transparency and traceability. Caution is recommended when presenting and interpreting results based on one or optional elements as majority of the methodologies related with these elements are based on subjective data and value judgement may come into effect[34]. The three elements are briefly described below:

Normalization is defined in ISO 14044 as process of "*calculating the magnitude of category indicator results relative to reference information*." The purpose of normalization is to contextualize impact results to improve understanding of their relative magnitude. This aids in identifying key contributors, checking for inconsistencies, and preparing results for further analysis such as grouping, weighting, or interpretation.

[33] Intergovernmental Panel on Climate Change. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

[34] Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., & Kendall, A. (2016). Pavement Life Cycle Assessment framework (No. FHWA-HIF-16-014). United States. Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/38470/dot_38470_DS1.pdf

Normalization transforms each impact indicator result by dividing it by a reference value making it unitless. ISO 14044 standards provide guidance on the comparison and normalization of LCA results. Normalization is not recommended when results are to be disclosed publcially. Likewise, when the data are incompatible, or data transparency is essential normalization needs to be avoided. Two main methods to normalize LCIA results are through: internal normalization and external normalization.

Internal normalization is used to compare two or more products within the same study. This kind of normalization is suitable for comparative studies. There are numerous methods for internal normalization, that can in form of simple division, application of a multi-criteria decision-making method (MCDM), or outranking[35]. This normalization enables ranking of alternative design options. The most common method to perform internal normalization is expressing each impact category as the percentage of total impacts. **Figure 5-3** provides an example of how impacts calculated based on characterization factors for alternative pavement designs are normalized by division.[36] The normalization in this example is applied for pavements of a 30-year lifecycle; however, normalization would be unsuitable for impacts if the system boundary only included phases A1-A5.

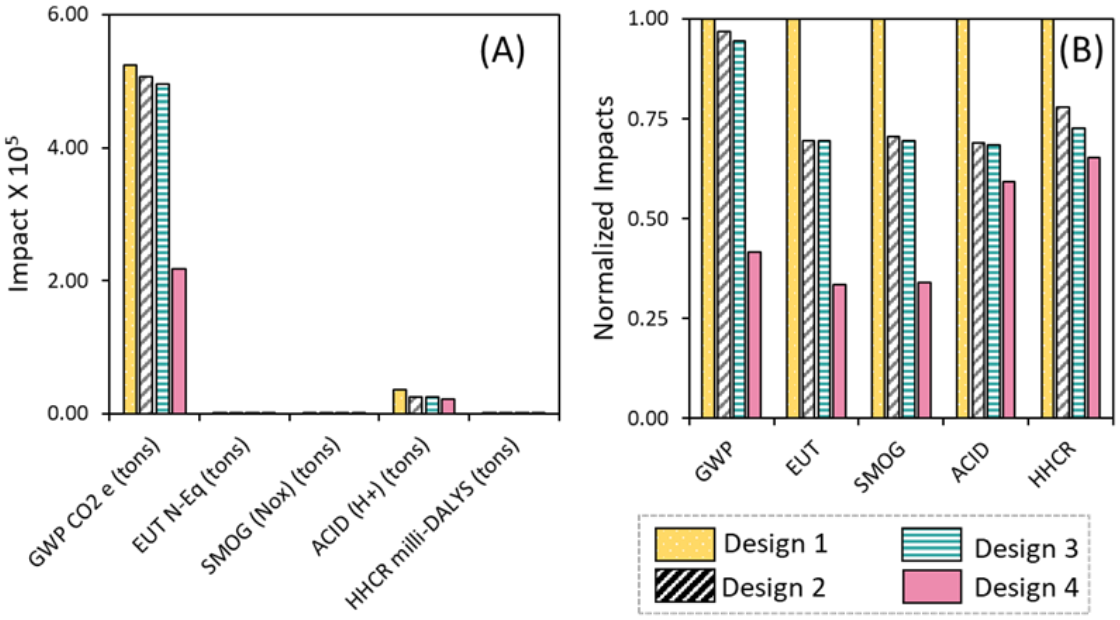


Figure 5-3: An example of (A) Characterized Impact Categories and (B) Normalized Impact Categories for four alternative pavement designs[40]

External normalization is used to assess how the impacts relate world problems and references data external to the study. It compares LCIA results to reference data outside the study, such as regional or national emissions inventories. This provides context on how the impacts relate to broader environmental burdens. However, external normalization relies on regional reference

[35] Prado, V., Rogers, K., & Seager, T. P. (2012). Integration of MCDA tools in valuation of comparative Life Cycle Assessment. Life Cycle Assessment handbook: A guide for environmentally sustainable products, 413-432.
[36] Inti, S., Sharma, M., & Tandon, V. (2016). An approach for performing Life Cycle Impact Assessment of pavements for evaluating alternative pavement designs. Procedia Engineering, 145, 964-971. https://doi.org/10.1016/j.proeng.2016.04.125

datasets, which are limited and may vary by geography and inventory year. For example, TRACI 2.1 normalization factors are based on combined inventories for the United States and Canada using reference years 2005–2008. Because regionalized impact references are not consistently available for many impact categories (e.g., air pollution and water pollution), external normalization is rarely applied in practical bridge LCA studies. Therefore, bridge LCAs typically rely on internal normalization to compare alternatives and identify key impact contributors.

The external normalization factor is calculated by ***Equation 5.2***

$$NF_i = \frac{\sum CF_{i,s} x E_s}{P} \qquad \textit{Equation 5.2}$$

Where:

NF_i normalization factor (impact capita^{-1} year^{-1}) for impact category i

$CF_{i,s}$ characterization factor (impact kg-1 emitted of a given substance s) for impact category i

E_s emissions of substances for a given geographical reference area (kg year-1)

P human population of the reference area (capita)

Table 5-1 provides the external normalization factors for TRACI 2.1 for US-CA geographical boundaries. As the table indicates these factors are restricted US and Canada and year 2005/2008 inventories. With change in region and inventory data these factors will be changed.

Table 5-1: TRACI 2.1 normalization factors for combined inventory of US and Canada with reference years 2008 and 2005 respectively[37]

Impact Category	Impact per year	Impact per person year
Global Warming Potential (kg CO2 eq)	8.0 X 10^{12}	2.1 X 10^{4}
Acidification Potential (kg SO2 eq)	3.2 X 10^{10}	9.5 X 10^{1}
Eutrophication Potential (kg N eq)	7.00 X 10^{9}	2.1 X 10^{1}
Ozone Depletion Potential (kg CFC-11 eq)	4.9 X 10^{7}	1.5 X 10^{-1}
Photochemical Ozone Formation (kg O3 eq)	4.9 X 10^{11}	1.5 X 10^{3}
Respiratory Effects (kg PM2.5 eq)	1.0 X 10^{10}	3.0 X 10^{1}
Carcinogens-Non-metals (CTUcanc.)	1.7 X 10^{3}	5.1 X 10^{-6}

[37] Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy, 16, 329-339. https://doi.org/10.1007/s10098-013-0629-z

Carcinogens-Metals (CTUcanc.)	1.5×10^{4}	4.3×10^{-5}
Non-Carcinogens-Non-metals (CTUnon-canc.)	1.1×10^{4}	3.4×10^{-5}
Non-carcinogens-Metals (CTUcanc.)	3.4×10^{5}	1.0×10^{-3}
Ecotoxicity- Non-metals (CTUe)	2.5×10^{10}	7.4×10^{1}
Ecotoxicity-Metals (CTUe)	3.7×10^{12}	1.1×10^{4}
Fossil Fuel Depletion (MJ surplus)	6.6×10^{12}	1.9×10^{4}

Grouping is defined in ISO 14044 as "*the assignment of impact categories into one or more sets as predefined in the goal and scope definition*." Grouping can involve sorting and ranking steps and needs to be interpreted with caution as value judgement is involved. This optional step facilitates value-based decision-making and can improve clarity in communicating LCA results.

In bridge LCA, grouping can simplify complex results and highlight key trade-offs between design options. For instance, categories can be grouped into air emissions, water use, and material depletion, and then ranked according to stakeholder priorities. A bridge authority may prioritize global warming, human health, and water consumption while considering land use and acidification as lower priority.

Table 5-2: Some common procedures for grouping of impact categories[38]

Procedure	Type of Grouping	Example	
Nominal	Geographic scale grouping	Global impacts	Climate Change, Fossil Fuel Depletion
		Regional impacts	Acidification, Photochemical Smog
	Impact typology grouping Inputs Outputs	Ecological health	Climate Change, Acidification
		Human Health	Photochemical Smog
		Resource use	Fossil Fuel Depletion
Hierarchal ranking	Ranking categories (based on perceived importance)		high, medium, low priority

Weighting involves conversion of impact indicators results into weighted results using numerical factors collected from expert judgement. The weighting can be applied either to impact results (or

[38] Venfitti, R.A. (2016) Lecture 14: Normalization, Weighting and Aggregation to Single Score Environmental Life Cycle Assessment PSE 476/FB 576

normalized results) or weights can be aggregated to get single end-point results or single scores. Since weights are based on value judgement the weights will vary with individuals, organizations and societies. The consequences of different weighing schemes are hence used in LCA study performing sensitivity analysis. In addition, whenever weighting is performed for an LCA study, the results prior to normalization and weighting need to be shared. This ensures all information related to actual impacts and potential trade-offs is available to the stakeholders and extent of environmental impacts is fully understood.

There are three methods to attain weight factors: the distance target method, the analytical hierarchy process, and the comprehensive index method. Chen et al.(2025)[39] used questionnaire methods and expert scoring to attain weighting for ecological index method for bridge LCA. Experts were categorized into three groups based on subjective factors that effected the weighting outcome (**Table 5-3**).

Table 5-3: Numerical weight factors of ecological index method used in Bridge LCA study[10]

Impact Category	Individualism (%)	Egalitarianism (%)	Hierarchy (%)
Ecological environment	25	50	40
Human health	55	30	30
Resources and energy	20	20	30

5.3 Other Considerations

LCIA can be an iterative process to ensure the goal, scope and the objectives of LCA study are attained. The project context influences the type of impact categories and LCIA methods to be considered. Multiple LCIA methods are in use globally. In North America, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)[40] is commonly applied, while International Reference Life Cycle Data System (ILCD)[41], ReCiPe[42], IMPACT World[43] and others are more common internationally. Since none of the method can cover all impact categories, needed by goal and scope of the study, use of two or more methods help ensure robustness of LCA results. Methodological choices and regional data variability can significantly influence results. For example, Dong et al. (2021)[44] showed that different LCIA methods yield

[39] Chen, X., Shi, P., & Wang, H. (2025). Life cycle environmental impact assessment of bridges based on comparison of different construction schemes. *Environment, Development and Sustainability*, 1-33. https://doi.org/10.1007/s10668-024-05895-6
[40] TRACI Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) | US EPA
[41] ILCD Handbook Draft recommended LCIA methods
[42] Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A.Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The international journal of Life Cycle Assessment, 22, 138-147. https://doi.org/10.1007/s11367-016-1246-y
[43] IMPACT World+
[44] Dong, Y., Hossain, M. U., Li, H., & Liu, P. (2021). Developing conversion factors of LCIA methods for comparison of LCA results in the construction sector. *Sustainability*, *13*(16), 9016. https://doi.org/10.3390/su13169016

different environmental profiles for construction projects. Similarly, Du and Karoumi (2013)[45] highlighted the importance of accounting for uncertainty in local data, especially in site-specific LCA studies for bridges.

Uncertainty in LCIA can stem from:

- Data quality from the LCI phase
- System boundary and cut-off decisions
- Functional unit changes, allocation methods, or averaging that may alter result's relevance

4.

[45] Du, G., & Karoumi, R. (2013). Life Cycle Assessment of a railway bridge: comparison of two superstructure designs. *Structure and Infrastructure Engineering*, *9*(11), 1149-1160. https://doi.org/10.1080/15732479.2012.670250

6. Data and Model Aspects

LCA evaluates the environmental impacts associated with a product or process, with carbon emissions being one of the key impacts considered. Under the broader context of climate change, the significance of carbon emissions is well recognized, making it one of the most common impact categories assessed in LCA studies. This chapter provides guidance on data requirements and modelling procedures for quantifying greenhouse gas (GHG) emissions associated with bridge infrastructure life cycle assessment (LCA). The focus is on carbon dioxide equivalent (CO_2e) emissions as the primary climate change indicator used in infrastructure LCA studies. It covers data extraction from the bridge model, compilation of a bill of materials, collection of additional inventory data, and analysis to generate a bill of flows. These steps enable a precise assessment of resource consumption, energy use, and waste generation throughout the bridge's life cycle. The quantification methods presented here adhere to ISO requirements (**Chapter 4**) for data collection and analysis. Like the NRC WbLCA[46], the resource flow framework suggests using a bridge element classification system for bridge data calculations.

The quantification of the Bridge Life cycle Inventory (LCI) should begin with the establishment of a comprehensive Bill of Materials (BoM) for each bridge element and component across all phases of the bridge life cycle model (see **Chapter 2**). This step involves creating a BoM that details the product quantities composing the physical structure. This process should align with the study's goal and scope, ensuring data collection consistency. In addition to material quantities, relevant metadata—such as material specifications, sources, and manufacturing details—should be documented to enhance data accuracy and transparency. The aim is to provide inventory data for the input and output categories (as listed in **Table 4-1**). From a bridge design and construction project, the following general data can be collected, where available:

6.1 Quantifying the Bridge Data

Quantifying the bridge data follows a two-step approach:

6.1.1 Itemize the Bridge Elements

The first step involves creating a an LCA model showing all unit processes and their interation to show inputs and outputs related with each. BoM is relevant for attaining this model and can help ensure all relevant processes in the system boundary are included. BoM details the product quantities composing the physical structure. The information hierarchy includes::

a) Bridge Elements: Define these elements to represent major bridge components, such as decks, girders, and piers. They are recommended as the primary units for assessment scoping (see **Chapter 2**).

b) Work Results: These refer to construction activity outputs, such as rebar placement, concrete pouring, and steel fabrication.

[46] Bowick, M., O'Connor, J., Salazar, J., Meil, J., & Cooney, R. (2022). National guidelines for whole-building life cycle assessment. Ottawa: National Research Council Canada. https://doi.org/10.4224/4000274

c) Product Inputs: Each work result comprises necessary product inputs, which include key descriptors (e.g., material grade/type, thickness), units of measure (e.g., tonnes), and metadata such as density and material specifications. Instead of specifying manufacturers, product types are identified to facilitate the selection of environmental data. For example, **Figure 6-1** illustrates an example of a bridge substructure element, a bridge pier (with pile and pile cap), and includes details required to perform LCA, such as concrete mix design, reinforcement quantities, and construction techniques. Depending on the goal and scope, these details can be expanded, along with those in other components. Similar or more detailed information is to be determined for other components of the bridge

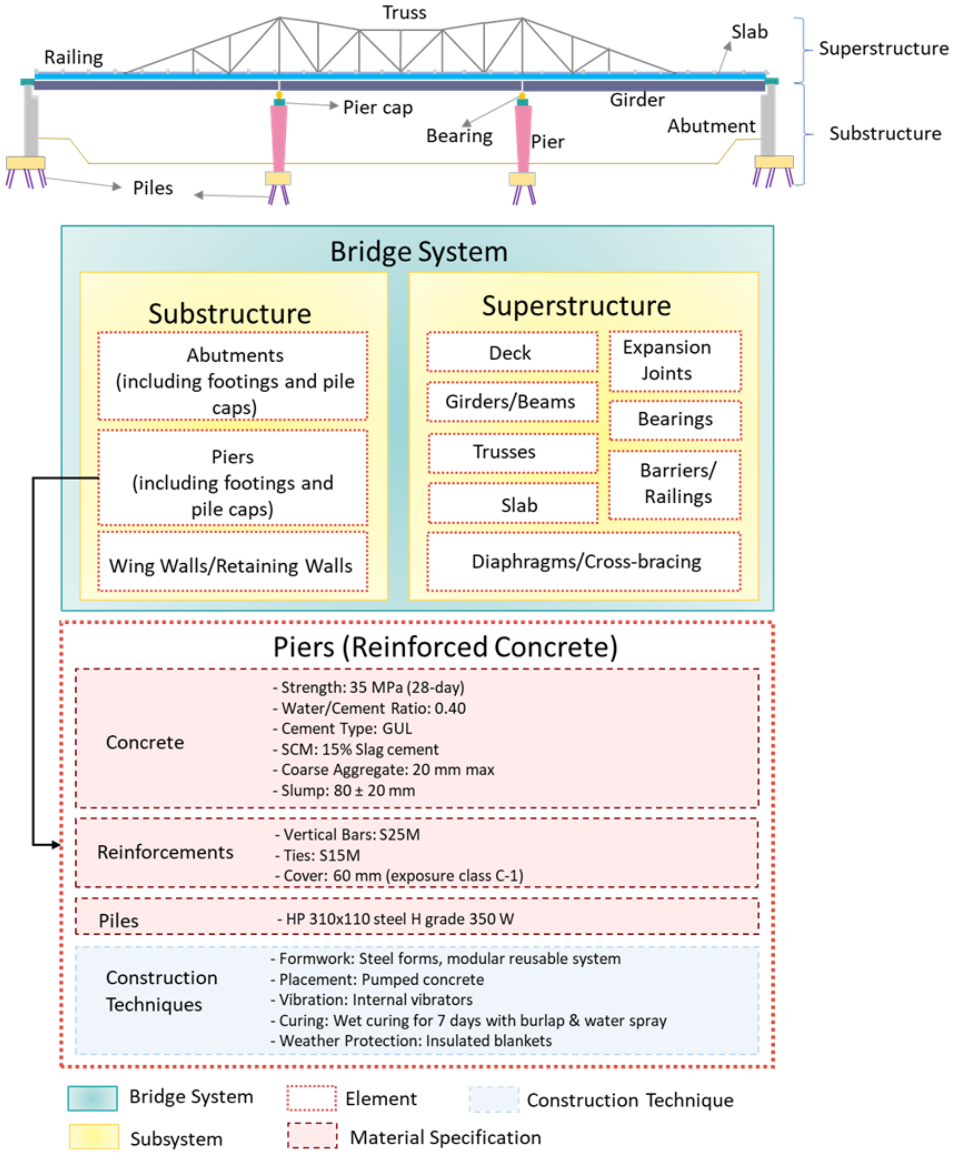


Figure 6-1: Itemize Bridge Element (Reinforced Concrete Pier) for Bridge Data Collection.

Note: each element of the bridge will be expanded with related inventory details

6.1.2 Obtaining Product Quantities

A number of methods for determining product quantities are available and their use depends on the design phase and available data sources. The source of data needs to be carefully documented to help understand data quality and interpretation of results. Common approaches include:

1. Calculations Based on Design Plans: Use available engineering plans to determine material quantities. Material quantities are manually or digitally extracted from project plans.
2. Conceptual Design Estimates: When design plans are unavailable, estimate material quantities based on standard bridge design criteria.
3. Bridge Information Modeling (BrIM): A digital modelling approach that refines details as the design progresses. It allows automated extraction of material quantities and component attributes from parametric bridge models. When available, BrIM models can significantly improve LCI accuracy by enabling direct quantity take-offs for structural elements such as concrete volumes, reinforcement tonnage, and steel member weights. BrIM can help categorizes elements and generate material quantities. Practitioners should verify that BrIM-generated quantities align with the LCA system boundary and ensure that temporary materials or construction aids are included where relevant.
4. Cost Estimation: Bridge engineers estimate material usage based on classification systems tailored to different project phases.

This structured methodology ensures consistency and transparency in bridge LCI data collection.

The BoM is considered complete once product quantities for all bridge elements within the defined scope have been compiled.

6.2 Models and Data Sources

This step focuses on procedure for calculating emissions data depending on the stage of the bridge life cycle (see **Figure 3-1**) and the method used to obtain bridge data.

6.2.1 Pre-construction (A0)

Pre-construction Module A0 is often omitted from most LCA studies but may become significant for infrastructure projects. The activities in this phase are closely related with material production modules. A0 emissions are generally small relative to material production but may be included for completeness depending on study scope. The module should thoroughly assess the consumption of resources related to travel, digital activities, and other areas prior to the commencement of construction. For practical implementation, A0 assessment should focus on activities with clearly quantifiable energy or fuel use, such as field investigations and travel associated with site visits or coordination meetings. Data may be estimated using project documentation, travel distances, typical vehicle fuel consumption, and equipment used during investigations.

Office-based design work and digital activities are generally expected to contribute relatively small emissions and may be excluded or represented using simplified assumptions where necessary.

This approach allows the A0 module to capture key pre-construction impacts while maintaining a practical level of data collection for infrastructure projects

.

6.2.2 Material Production (A1 – A3)

The materials production stage is the first physical process phase in Bridge LCA. When only this stage is assessed, the study is referred to as a cradle-to-gate LCA. This stage includes the extraction of raw materials, processing, transportation, and storage up to the point where materials reach the manufacturing facility. Each material follows its own life cycle, so data collection must encompass all relevant materials within the system boundary, except for those excluded based on cut-off criteria. For prefabricated elements, the gate stage includes all activities that result in a finished product, not just the raw materials. This means formwork, curing, reinforcement, cast-in inserts, and any other processing required to produce the element are already captured in A3.

It is important for users of this guide to understand that prefabricated elements should not be treated as individual materials in the LCA, but rather as finished construction products whose A1–A3 impacts account for all internal processes. In contrast, site construction activities (A4–A5) cover transport to site, handling, and assembly, which are outside the gate.

6.2.2.1 *Data Collection*

The following methods can be used to obtain life cycle inventory for materials used in bridge construction:

- Direct Data from Manufacturers: Obtain emissions data directly from the producer through measurements
- Environmental Product Declarations (EPDs): Product-specific or industry-average EPDs may be used as primary data sources for material production stage(modules A1–A3) emission factors.. it is important to select EPDs that match the specific strength and type of the materials or prefabricated elements being used. EPDs contain information on transportation involved until product manufacturing stage.. Type III EPDs, provide independently verified and product-specific environmental information and provide the highest accuracy. It is therefore recommended to use Type III EPDs whenever available. For prefabricated elements such as precast panels, EPDs typically report impacts per tonne of finished product, including reinforcement, inserts, and all internal processing. Users should ensure that the EPD corresponds to the same product category and that units are consistent with the BoM to avoid double-counting. The guide references ISO 14025, which defines the standard for Type III EPDs and clarifies the expected level of quality and transparency. For practical project implementation, the conservative approach is to collect EPDs at the product level aligned with the BoM; this allows practitioner to scale impacts based on quantities without requiring detailed knowledge of direct measurements or CEMS data. EPDs should conform to ISO 14025 Type III EPD requirements and relevant product category rules (PCRs). When using EPDs, practitioners should ensure:

- declared units match the material quantities used in the project
- geographic representativeness is appropriate for the project location
- the system boundary of the EPD aligns with the LCA scope
- If multiple EPDs are available for the same material category, a representative value (e.g., average or conservative selection) should be documented.

- Modeled emissions using known material quantities: Use industry databases or emission factors to estimate emissions based on the composition of materials. This will require mapping product inputs (from BoM) to LCI datasets.
- Comparison with Similar Bridges: Use the design of a comparable bridge to approximate material use and associated emissions.
- Literature-Based Data: As a last resort, refer to LCA studies of similar structures in published literature to estimate emissions.

6.2.2.2 *Emissions Calculation*

To model impacts from A1–A3:

- Aggregate material-level emissions using mass-based quantities from the project's BoM
- Transport impacts from moving raw materials to construction plant (A2) can become relevant and need to be assessed carefully. Please refer to Section **6.2.3. for A4.** The impacts of A2 will be calculated using same method.
- Handle co-products using allocation methods per ISO 14044:
  - Mass-based (default for most construction LCAs)
  - Energy-based (where processes are energy-driven)
  - Economic value-based (for complex industrial processes)

Clearly document allocation choices and apply them consistently across material flows.

For example, to calculate GHG emissions from A1–A3 for materials without specific EPDs, a practitioner can estimate GHG emissions using *Equation 5.1*:

$$GHG\ Emissions_{A1-A3} = \sum_{i=1}^{n} Q_i \times EF_i$$

Equation 6.1

Where:

Symbol	Description

Q_i	Quantity of material *i* (e.g., tonnes or m³) from BoM
EF_i	Emission factor for material *i* (for example, kg CO_2e per unit)
n	Number of material types

When using EPDs:

- Match declared units (e.g., 1 m³ concrete, 1 tonne reinforcing steel) to project quantities
- Convert units as needed to ensure compatibility

6.2.3 Transport to Site (A4)

Module A4 covers the environmental impacts of transporting construction products and materials from the manufactuiring facilities to the bridge construction site. Include transportation distances for landscaping materials, particularly soils and nursery plants, which can be mass- and volume-intensive. This includes direct fuel combustion and upstream emissions from fuel production and delivery (often referred to as well-to-tank emissions). These upstream emissions are typically accounted for through life-cycle emission factors provided in LCA databases or national emission factor datasets.

Transport modelling should explicitly identify the following parameters for each material flow:

- origin location
- transport mode (truck, rail, marine, etc.)
- transport distance
- vehicle load factor
- return trip assumptions

When project-specific logistics information is unavailable, representative transport distances and load factors may be assumed using regional freight statistics or published literature.

6.2.3.1 *Data Collection*

To model transportation impacts, it's essential to:

- Identify transport modes: Determine whether trucks, trains, ships, or other methods are used for each product or material. Consider all transport legs from the point of manufacture to the bridge construction site.
- Gather data:
    - Transport distance between origin and delivery point (km) (production sites and the bridge construction site)
    - Vehicle type and fuel type (e.g., diesel semi-trailer, electric rail)
    - Load factor or utilization rate, based on expected average payload

- Return trip assumptions, including whether backhaul is empty, partially loaded, or fully utilized
- Multi-leg transport chains, such as manufacturer → depot, → bridge site.

6.2.3.2 *Emission Calculation*

Modelling transportation emissions should be guided by the following protocols:

- Use relevant and reputable emission factor databases such as the National Inventory Report (NIR) Canada[47], Ecoinvent[48], USLCI[49], Transportation carriers, The GHG Protocol website[50], Industry associations (e.g. Railway Association of Canada[51])and organizations (International Maritime Organization, Clean Cargo Working Group, etc.)
- Express emissions per tonne-kilometre or cubic metre-kilometre, depending on material type
- Disaggregate transport by material when logistics vary between products
- Account for multi-leg transport chains (e.g., manufacturer → regional depot → construction site), modelling each leg separately
- Backhaul Assumptions: include emissions from unladen return trips, indicating these in the calculations.

Two methods are commonly used for calculating emissions, depending on data availability: fuel-based and distance-based. Both align with ISO 21930[52] and the GHG Protocol Scope 3 Standard. The fuel-based method is generally more accurate than the distance-based method in calculating GHG emissions, as fuel consumption directly correlates with emissions. However, if allocation data is unavailable or unreliable, such as in cases where multiple goods are transported in the same vehicle simultaneously, the distance-based method becomes the preferred alternative for estimating Module A4 emissions.

Option 1: Fuel-Based Method

- Approach: If data on fuel use is available, this method is recommended for its accuracy. Emissions are calculated directly from fuel consumption records, which are closely tied to greenhouse gas outputs.
- Data Sources: Where fuel use data is unavailable, the company may derive fuel use by using
  - Fuel purchase receipts,

[47] National inventory report: greenhouse gas sources and sinks in Canada National inventory report : greenhouse gas sources and sinks in Canada.: En81-4E-PDF - Government of Canada Publications - Canada.ca
[48] Ecoinvent ecoinvent - Data with purpose.
[49] U.S. Life Cycle Inventory Database U.S. Life Cycle Inventory Database | Energy Analysis | NREL
[50] GHG Protocol tools Calculation Tools and Guidance | GHG Protocol and Corporate Value Chain (Scope 3) Standard | GHG Protocol
[51] Railway Association of Canada Locomotive Emissions Monitoring Program 2015-LEM-Report.pdf
[52] ISO 21930:2017 - Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services

- Distance travelled and the vehicle's fuel efficiency,
- Transportation service invoices, or
- Data from transport management systems.

- Emission Factors: Reference databases like the National Inventory Report (Canada), Part 2 Annex 6[53], for factors associated with different mobile combustion sources. Where life-cycle emission factors are used, they may already include upstream emissions from fuel extraction, refining, and distribution. If combustion-only emission factors are applied (e.g., from national inventories), upstream emissions can be added separately using well-to-tank emission factors from life-cycle databases such as Ecoinvent, USLCI, or other recognized LCA datasets.
- Calculation: Emissions can be derived using the vehicle's fuel efficiency, distance travelled, and average fuel costs.

GHG emissions can arise when hauling materials (trucks, rail, or barge) for a specified distance.

$$GHG\ Emission_{A4} = \sum_{i=1}^{n} \frac{D_i}{FE_j} \times EF_{ijk}$$

Equation 6.2

Where:

Symbol	Description
D_i	Distance material i was transported, in km
FE_j	Fuel Efficiency of transport mode/vehicle type j, in km/L, Fuel Efficiency Benchmarking in Canada's Trucking Industry estimate[54] can be used for fuel efficiency
$EF_{i,j,k}$	Emission factor for transport mode j fuel type k to transport material i, in g CO2/l

Option 2: Distance-Based Method

- Approach: When fuel data is unavailable, use this method by multiplying transport distance by the mass or volume of goods transported and an appropriate emission factor that incorporates average fuel consumption, average utilization, average size and mass or volume of the goods and the vehicles, and their associated emissions.
- Emission Factors: Typically measured in grams or kilograms of CO_2 equivalent per tonne-kilometre or cubic-meter-kilometre.

[53] National Inventory Report En81-4-2020-2-eng.pdf
[54] Fuel Efficiency Benchmarking in Canada's Trucking Industry - Natural Resources Canada

- Calculation: This method uses average utilization rates, transport mode-specific factors, and standard emissions databases such as Ecoinvent or USLCI

GHG emissions can arise when hauling materials (for a specified distance using trucks, rail, or barge.

$$GHG\ Emission_{A4} = \sum_{i=1}^{n} Material\ Quantity_i \times D_i \times EF_{i,j,k}$$

Equation 6.3

Where:

Symbol	Description
$Material\ Quantity_i$	Quantity of Material i (including basic ingredient, component mixture, and waste) transported, in tonne or m^3
D_i	Distance material i was transported, in km
$EF_{i,j,k}$	Emission factor for transport mode j vehicle type k to transport material i, in g CO2/tonne-km or m^3-km

Where available, ***Equation 5.3*** can be modified to consider emission factors (in g CO2/tonne-km) that vary with deadhead percentage and load quantity for trucks, rail and barge. Data quality should always be checked for temporal and spatial relevance compared to other available data for more accurate estimates.

Data sources for the emission factor include:

- Transportation carriers
- International Government agencies (e.g., US EPA[55] e.tc.)
- International Organizations and Industry associations (e.g., GHG Protocol, International Maritime Organization)
- Literature: Use recent Ontario-based freight trucking emission factors (g/km) from the study[56] done at the University of Waterloo, then adjust for loading (g/tonne-km), or use Canadian freight-based trucking value (g/tonne-km) from the University of Manitoba (Malzer 200557)

6.2.4 Construction and Installation (A5)

Module A5 should account for the environmental impacts of the construction and installation phase, encompassing site energy use, water consumption, temporary works, and material use required for installation activities (e.g., grout for prefabricated components, curing compounds,

[55] United States of America Environmental Protection Agency (US EPA) GHG Emission Factors Hub | US EPA
[56] Min, Q. (2020). Quantifying greenhouse gas mitigation measures during provincial highway design, construction, and maintenance activities (Master's thesis, University of Waterloo). http://hdl.handle.net/10012/16577
[57] Malzer, J. L. (2005). Aspects of energy use and emissions by heavy trucks (Master's thesis, University of Manitoba).

anchoring systems), as well as waste generated during construction. Mobilization and demobilization has a major contribution to emissions at this stage. Additional emission sources during construction may include explosives used in demolition or excavation activities and increased fuel consumption by road users due to traffic detours or construction-related congestion. Where these emissions are significant, they should be considered separately from direct construction equipment emissions

Three levels of modelling detail may be applied for construction emissions depending on data availability:

- Level 1 – Site-specific fuel consumption data

  Fuel logs or equipment monitoring data.

- Level 2 – Equipment operating estimates

  Equipment operating hours × fuel consumption rates.

- Level 3 – Activity-based modelling

  Material production rates and equipment productivity assumptions.

Practitioners should prioritize higher-quality site-specific data when available, but default assumptions and published fuel-use factors are typically sufficient for design-stage assessments

6.2.4.1 *Data Collection*

A5 module includes all the energy use, process information, including waste generated on site and its handling route (e.g., landfill vs. recycling) if available. Site activity emissions can be estimated from on-site electricity consumption and fuel use and should be monitored during construction to contribute to an accurate LCA calculation at practical completion.

In most infrastructure applications, LCA is conducted during the planning and design stages, using estimated construction activity data derived from construction schedules, equipment productivity assumptions, and typical fuel consumption factors. These estimates allow practitioners to evaluate the relative impacts of alternative construction approaches and materials before construction begins.

Where available, site-specific construction data—such as contractor fuel logs, equipment monitoring systems, or temporary electricity records—may be used to refine A5 estimates or improve future datasets. However, detailed monitoring during construction is not required for most project-level LCAs and should be considered optional.

Construction Equipment and Activities

- Identify machinery and equipment used (e.g., cranes, concrete pumps)
- Where possible, collect site-specific data from:
  - Contractor logs or construction management platforms (when available)
  - Equipment manufacturer data on fuel/electricity consumption (fuel types and consumption rates)
  - Utility bills or temporary power connection records

    - Interviews with project engineers or foremen
    - Temporary facilities (e.g., site offices, lighting)
- When direct data is unavailable, estimate emissions using:
    - Review construction schedules for activity intensity and duration
    - Fuel Usage Factors (FUFs) for typical machinery and operating conditions
    - Case studies or LCA databases for similar bridge types
    - Published literature and benchmark construction projects
- Quantify energy consumption from:
    - Electricity (e.g., tower cranes, lighting, heating)
    - Diesel or gasoline (e.g., excavators, trucks, concrete pumps)
    - Natural gas or propane (e.g., heating, curing)
- Select and apply relevant emission factor compactible with calculation method with collected data

Electricity: Use province-specific Electricity emission factors obtained from the most recent National Inventory Report58 (NIR) tables for provincial electricity consumption intensities, rather than generation intensities, to reflect net imports and exports of electricity. Practitioners may alternatively use a fixed NIR version if consistency of background datasets across the study is required Fuel combustion: Use factors sourced from the most recent NIR fuel combustion tables, unless a consistent background dataset is intentionally maintained across the analysis.

Landscape Construction

- Where landscaping is considered a functional part of the scope of the bridge LCA, for example a crossing bridge for animals that includes landscaping of the entire bridge deck, its important to:
- Estimate material quantities (soil volume, plant counts, piping lengths, etc.) based on landscape design plans or as-built documentation.
- Include fuel and equipment use for excavation, soil placement, and irrigation installation—such as compact loaders, trenchers, and small cranes.
- Account for temporary features such as erosion control mats or planting supports if not removed.

6.2.4.2 *Emission Calculation*

[58] Environment and Climate Change Canada (ECCC). (2025). National inventory report 1990–2023: Greenhouse gas sources and sinks in Canada. Part 3: Annexes 8 to 13. Government of Canada. https://publications.gc.ca/site/eng/9.506002/publication.html

Three approaches are provided here:

Fuel-Based Emission Calculation

This is the most common approach and simpler inventories calculation where fuel logs are available. However, it can be less accurate for multi-equipment project unless disaggregated. Idle time and load factor variations are also ignored. An example to calculate GHG emission, the amount of fuel use for each type of equipment is multiplied by the corresponding emission factor as:

$$GHG\ Emission_{A5} = \sum_{i=1}^{n} F_i \times EF_j$$

Equation 6.4

Where:

Symbol	Description
F_i	Fuel consumption of equipment i (litres or kg)
EF_j	Emission factor for fuel type i (kg CO_2e per litre or kg)
n	Number of fuel types or equipment categories

Use equipment-specific fuel usage factors (FUFs) where direct consumption data is unavailable, considering engine load and operating conditions. FUFs, which estimate fuel consumption in various construction activities is in a summary table in Appendix A. The table summarizes FUF values for different equipment types and conditions, helping in environmental impact assessment and life cycle analysis. Key factors influencing FUFs include engine load, operating conditions, and equipment type. The summary helps optimize fuel consumption, reduce costs, and minimize emissions.

Electricity-Based Emission Calculation

For electrically powered construction equipment (e.g., electric cranes, pumps, battery-electric vehicles), the National Inventory Report: greenhouse gas sources and sinks in Canada 2020, Part 3 Table A13-2 to A13-14 for provincial greenhouse gas emission intensity for consumption can be used to calculate emissions from electricity use on site. Multiply the amount of electricity used by the province's emission factor.

$$GHG\ Emission_{A5} = \sum_{i=1}^{n} EEE_i \times EF_i$$

Equation 6.5

Where:

Symbol	Description
EEE_i	On-site electricity use (kWh)

EF_i	Emission factor for electricity in project's province (kg CO_2e/kWh)

Refer to NIR 2020 Part 3 Tables A13-2 to A13-14 for regional electricity emissions intensity.

Activity-based (engine power–based) emissions estimation

This is commonly called the "engine activity method" or "horsepower-hour approach", used in estimating emissions from construction machinery and other nonroad engines. This method is adapted from the U.S. EPA NONROAD[59] the model was developed for estimating emissions from nonroad equipment (e.g., bulldozers, pavers, excavators). It is commonly used in LCA, GHG inventories, and road infrastructure LCA tools such as FHWA's LCA Pave tool[60], PaLATE[61], Athena Pavement LCA Tool[62]. Use the most recent National Inventory Report: greenhouse gas sources and sinks in Canada or the US Environmental Protection Agency GHG Emissions Factors Hub for non-road or off-road vehicle emission factors.

To calculate emissions based on the horsepower-hour approach, use:

$$GHG\ Emission_{A5} = \sum_{i=1}^{n} \frac{Material\ Quantity_i}{Productivity_j} \times Power_j \times LF_j \times EF_j$$

Equation 6.6

Where:

Symbol	Description
$Material\ Quantity_i$	Quantity of Material (e.g. hot mix asphalt, recycle material, etc.), in tonne, m^2, or m
$Productivity_j$	Productivity of the construction equipment j, in corresponding material quantity process per hour
$Power_i$	Average power of the construction equipment j, in hp
LF_j	Load Factor (fraction of available power) of the construction equipment j
EF_j	Emission factor for construction equipment j, in kg CO_2/hp-hr

[59] MOVES Nonroad Technical Reports | US EPA
[60] Pavements - Federal Highway Administration
[61] PaLATE - Pavement Life-cycle Tool
[62] Pavement LCA | Life Cycle Assessment Software

To calculate emission using engine activity method, use;

$$GHG\ Emission_{A5} = \sum_{i=1}^{n} \frac{Material\ Quantity_i}{Fuel\ Consumption\ per\ output_j} \times Production\ Rate_j \times LF_j \times EF_j$$

Equation 6.7

Where:

$Material\ Quantity_i$	Quantity of Material (e.g., hot mix asphalt, recycle material, etc.), in tonne, m^2, or m^3
$Fuel\ Consumption\ per\ output_j$	Fuel consumption of the construction equipment j, in corresponding material quantity process per hour, in L/hr
$Production\ Rate_j$	Average production rate of the construction equipment j, in volume or area per hr (m^3/hr or m^2/hr)
LF_j	Load Factor (fraction of available power) of the construction equipment j
EF_j	Emission factor for construction equipment j, in kg CO_2/L

Waste Handling

Estimate emissions from waste disposal routes:

- Recycled materials (minimal emissions; may be credited depending on methodology)
- Landfilled materials (include disposal transport and decomposition emissions if relevant)
- Use site waste audits or average waste generation rates from comparable projects.

6.2.5 Use/Operation (B1)

In **Section 3.4.3** of this Guideline, several environmental aspects of the use phase of bridge infrastructure are discussed; however, this section provides LCI guidance for only four key aspects.

1. *Vehicle-Structure Interaction*

Although the bridge structure itself does not consume energy during use, it indirectly affects vehicle operation through surface condition, ride quality, and gradient. As part of the goal and scope, practitioners may consider modelling the influence of bridge deck conditions on vehicle fuel consumption and emissions.

Existing vehicle operating energy and rolling resistance models may be applied using surface condition data, such as International Roughness Index (IRI) or rutting measurements. These are typically relevant in longer-span or approach structures where surface wear could have a measurable impact over time.

The following approaches are recommended:

I. Preferred: Use traffic volume and load data combined with bridge deck condition metrics to estimate changes in vehicle energy use over time.

II. Alternative: Use regional or project-specific deterioration models to estimate future roughness, then apply vehicle operating models to estimate the impact on emissions or energy use.

III. Simplified: Assume average traffic and pavement performance values based on similar bridge types in similar environments, noting the assumptions used.

Practitioners are directed to literature sources[63][64][65] and the FHWA Pavement LCA Guideline[66], where guidance is available on selecting Pavement-Vehicle Interaction models to quantify the impacts of this aspect.

2. Drainage Systems

Bridge drainage systems are designed to protect the structure from water-related degradation and to manage surface runoff. Use-stage impacts may arise from:

- Stormwater collection and conveyance
- Potential treatment (e.g., separators, filters)
- Energy use (e.g., for sump pumps, if applicable)

If included in the scope, runoff pollutant loads can be assessed using empirical models or direct sampling. Pollutants of concern include de-icing chemicals, sediments, and hydrocarbons. Data-Driven Models (DDMs) or existing water quality datasets may also be used to estimate pollutant concentrations and flows.

3. Lighting and Signage

Electricity use is the primary operational impact for bridges equipped with lighting or electronic signage. Measurement approaches include:

- Direct metering: Where dedicated energy meters are available for bridge lighting systems.
- Modelled estimation: Based on fixture type (e.g., LED, high-pressure sodium), rated power consumption (watts), and operating hours.

[63] Santos, J., Miller, S. R., & Cerezo, V. (2022, November). Pavement vehicle interaction (PVI): the elephant in the pavement Life Cycle Assessment (LCA) room. In CROW Infradagen 2022.
[64] Mahajan, G. R., Radhika, B., & Biligiri, K. P. (2022). A critical review of vehicle-pavement interaction mechanism in evaluating flexible pavement performance characteristics. Road Materials and Pavement Design, 23(4), 735-769. https://doi.org/10.1080/14680629.2020.1860806
[65] Mattinzioli, T., Butt, A. A., & Harvey, J. (2023). Literature review on pavements and electric vehicle interaction: A research roadmap. Transportation Research Part D: Transport and Environment, 122, 103886. https://doi.org/10.1016/j.trd.2023.103886
[66] Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., & Kendall, A. (2016). Pavement Life Cycle Assessment framework (No. FHWA-HIF-16-014). United States. Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/38470/dot_38470_DS1.pdf

For example, a 120-watt luminaire operating 12 hours per night over a year would consume approximately 525.6 kWh annually. These values can be scaled according to the total number and type of fixtures on the structure.

4. *Movable Bridge Operations (Lift, Bascule, Swing Bridges)*

For bridges that incorporate mechanical systems to facilitate movement, such as lift bridges, bascule bridges, or swing bridges, the energy consumed during the operation of these systems constitutes a significant use-stage impact.

These energy demands are primarily related to:

- Electric motors or hydraulic systems used to lift or rotate bridge segments
- Control systems and lighting during operation
- Ancillary systems such as barriers, alarms, and operator cabins

Key considerations for assessing energy use in movable bridge operations include:

- Number of openings/closings per year: This can vary widely depending on marine traffic frequency. Historical operation logs or scheduling records should be used where available.
- Energy consumed per cycle: Typically provided by the equipment manufacturer or obtained via metering of the motor systems. If unavailable, estimate based on motor rating (kW) and average cycle duration (in minutes).
- Standby energy consumption: Some systems may consume power in idle mode (e.g., control systems, heating or lighting of operator cabins), which should be included if significant.

Optional enhancements to LCA modelling:

- Compare energy use between bridge types (e.g., bascule vs. lift vs. swing) if assessing design alternatives.
- Evaluate potential for energy recovery systems or efficiency improvements (e.g., replacing hydraulics with high-efficiency electric drives).

6.2.6 Maintenance (B2)

This is considered routine and seasonal maintenance. **Table 6-1** illustrates the LCI data requirements for some key activities and key data points. Maintenance activities represent recurring interventions required to preserve bridge functionality and serviceability during the operational life of the structure. This stage also incorporates impact related to re-mobilization if equipment to site for maintenance activities.

Typical maintenance activities include:

- joint sealing and replacement
- cleaning and inspection operations
- repainting or corrosion protection

- snow and ice control

Key points:

- The frequency of maintenance interventions should be derived from bridge management systems, asset management guidelines, or historical maintenance records (e.g., once/year for cleaning, every 5–10 years for coatings), bridge-specific maintenance logs or regional averages.
- Material quantities estimated from unit surface area (e.g., m^3 of railing, deck) and standard application rates (example: Annual mass of de-icing material applied (kg/year))
- Equipment types selected based on typical maintenance methods (e.g., diesel trucks, power washers, paint sprayers).
- Energy used by maintenance vehicles (litres of fuel or kWh)

The following assumptions could be applied in the LCI modelling: average regional emission factors are used for fuel consumption, such as diesel at 2.7 kg CO_2 per litre[67]. The average service life of recurring consumables—such as lightbulbs and protective coatings—is incorporated into the inventory to account for their replacement over the bridge's lifespan. Additionally, while the environmental impacts of salt runoff are excluded from the global warming potential calculations, they may be addressed qualitatively in the interpretation phase. In addition, salt runoff may have greater environmental imapcts for other categories such as eutrophication and acidification.

Table 6-1: Examples of LCI Data Requirements for Bridge Maintenance (B2)

Activity	Inventory Data	Parameter	Description
Joint sealing/coating reapplication	Type and quantity of sealants, coating materials, and application frequency	Joint sealant	kg per joint length (m); every 10–15 years
Painting of railings and other exposed metallic components (e.g., steel girders, brackets, connection plates).	Paint type, coverage rate, surface area, frequency	Paint (railings/coatings)	Litres per m^2; paint type (epoxy, alkyd), VOC content
Sandblasting	Abrasive material use, containment, energy use, and emissions	Sandblasting	kg of abrasive per m^2; energy use of compressors

[67] NRC (2014) Auto$mart - Learn the facts: Emissions from your vehicle (Factsheet 9). Office of Energy Efficiency

De-icing salt application	Salt type, annual quantities, spreading equipment, runoff impacts (if modelled)	De-icing salt	kg/m²/year; consider region-specific climate models
Snow removal	Equipment type; Fuel consumption; Electricity use; Activity frequency	Type and number of vehicles/equipment used for clearing snow from the bridge deck; Amount of fuel each equipment type consumes per snow removal operation; Only if electric equipment is used; Number of times the bridge deck is cleared of snow per winter	Plow truck, snow blower, brush truck; Liters of diesel or gas per event; kWh (if electric snow blower); Events per winter season
Electrical systems maintenance	Lightbulb replacements, wiring checks, control panel servicing, energy use	Electrical maintenance	Annual kWh per lighting unit; expected service life of components

Other relevant activities are dependent on study goals and data availability

1. *Access and Inspection Activities*

Routine inspections and maintenance (e.g., joint cleaning, bearing lubrication, deck washing) may require fuel, electricity, or temporary structures. These impacts are often minor but should be included if:

- The LCA is highly detailed or at a component level, or
- Access structures (e.g., scaffolding or platforms) are significant recurring items

Estimations can be based on:

- Fuel use by maintenance vehicles or equipment
- Frequency and duration of activities
- Energy consumed by inspection tools (e.g., drones, sensors, lifts)

- *Fertilization and soil amendments*: Periodic application of fertilizers, compost, or soil conditioners. Include:
    - Type and quantity of fertilizer used per year

    - Transport emissions from fertilizer delivery
    - Emissions related to nitrogen release or runoff, if within scope
- *Plant maintenance and replacement*:
    - Fuel use and emissions from mowing, pruning, or trimming equipment
    - Replacement of plants due to mortality, vandalism, or seasonal changes
    - Disposal or composting of green waste
- *Pest and weed control*: Use of herbicides, insecticides, or manual control methods; consider active ingredient impacts and equipment emissions if applicable

Data collection strategies

- Use maintenance logs from transportation or municipal authorities
- Conduct interviews or site audits for frequency and type of maintenance activities
- Apply standard assumptions for small landscape elements based on landscape guidelines if direct data is unavailable

Landscaped areas on bridges often require specialized access, which may increase equipment use (e.g., lift trucks, crane baskets) or limit maintenance frequency—these constraints should be reflected in activity estimates. If bioswales or other green infrastructure features are present, additional activities such as sediment removal, plant replacement, and stormwater system flushing may be necessary and should be documented accordingly. Seasonal variability (e.g., winter dormancy) may affect irrigation and maintenance intensity.

6.2.7 Repair (B3)

B3 includes localized corrective actions due to unexpected deterioration or damage. These are typically unscheduled and vary in frequency and scale. Data sources include inspection reports, repair manuals, material specifications and contractor logs. **Table 6-2** provides an example of LCI data required for this module.

Table 6-2: Examples of LCI data and data points for bridge repair (B3)

Activity	Inventory Data	Parameter	Description
Crack sealing and patching	Crack filler type, patching material (mortar, epoxy), access equipment	Patching material	kg or m^3 per repair site; curing requirements (e.g., steam curing)
Recoating of structural steel components	No. of coats, cleaning method, corrosion level, coating material	Coating material	L/m^2 per repair area

	(zinc-primer, galvanizing material)		
Deck overlay	Material quantities (concrete, latex-modified concrete,), membrane system (sheet membrane, liquid membrane), reinforcement, bonding agent (epoxy, grout)	Overlay materials	kg or m³ per repair site
Waterproof membrane repairs	Material quantities (SBS modified bitumen, primer, adhesive), equipment	Membrane material	L/m^2 or deck area
Concrete or steel spot repairs	Material quantities, formwork, welding inputs, re-coating	Concrete repair	Includes bonding agents, demolition of the damaged zone, and waste management

6.2.7.1 *Data Collection*

- Derive frequency from asset management systems or deterioration curves.
- Estimate repair quantities as a percentage of the component area (e.g., 5–10% of deck patched every 20 years).
- Use standard repair mix designs (e.g., patching mortar, epoxy, welded steel).

In the absence of structure-specific data, average unit quantities are used to represent localized damage. Emissions from welding activities account for both direct energy use and associated consumables, such as flux and welding rods.

6.2.7.2 *Emission Calculation*

Emissions related to repair can be calculated using

$$GHG\ Emission_{B3} = m_i \times Material\ Quantity_i \times EF_i \times f_i$$

Equation 6.8

Where:

$Material\ Quantity_i$	Quantity of Material (e.g., patching mortar, epoxy, welded steel.), m^2, or ft^2
m_i	Percentage of area repaired per event (as a decimal)
EF_i	Emission factor for material repaired, in kg CO_2/m^2
f_i	Frequency of repair event

6.2.8 Replacement (B4)

Module B4 addresses the planned or reactive replacement of bridge components that have reached the end of their service lives. **Table 6-3** provides an example of LCI data required for this module.

Table 6-3: Examples of LCI data requirements for bridge replacement (B4)

Component Replaced	Inventory Data	Parameter	Description
Deck overlays/pavement surfaces	Material type and quantity (e.g., asphalt, waterproofing), milling, resurfacing energy	Deck overlays	Asphalt/concrete thickness × area; removal and resurfacing
Expansion joints drainage systems	Drainage components (PVC pipes, catch basins), removal and installation equipment	Expansion joint	Size, material quantities
Structural health monitoring systems	Quantity and type of sensors, power required collection, transmission and processing, energy source, removal and installation equipment	System details	No. of sensors, material quantities of sensor and collection, transmission and processing systems
Dampers / shock absorbers	Materials, removal and installation equipment	Dampers/ shock absorbers	Mass of dampers/ shock absorbers
Cathodic protection system	Anodes, conductive overlay, wiring and connections, monitoring components removal and installation equipment	Cathodic protection system	Mass of materials present in cathodic protection system
Bearings or railings	Component dimensions, material composition, removal and installation equipment	Bearing replacement	Type (elastomeric, steel-PTFE), quantity, jacking equipment used

6.2.8.1 *Data Collection*

- Use defined component service lives (e.g., 25 years for expansion joints, 50 years for bearings). Use industry-standard replacement intervals or project-specific inspection data, and apply average waste recovery rates based on national or regional construction and demolition waste recycling statistics where available,.
- Model demolition, replacement, and disposal flows explicitly.

- Estimate volume or mass based on standard bridge cross-sections.

For LCI development, assume industry-standard replacement intervals unless project-specific inspection data are available. Apply average waste recovery rates, m Typical recovery rates for construction materials should be based on national or regional construction and demolition waste recycling statistics68 where available, to reflect typical end-of-life material handling practices. Default recovery rates can be applied consistently throughout the assessment unless project-specific waste management data are available.

6.2.8.2 *Emission Calculation*

Emissions related to repair can be calculated using

$$GHG\ Emission_{B4} = Material\ Quantity_i \times EF_i \times f_i$$

Equation 6.9

Where:

$Material\ Quantity_i$	Quantity of Material (e.g., hot mix asphalt, recycle material, etc.), in tonne, m^2, or m^3
EF_i	Emission factor for material repaired, in kg CO_2/m^2
f_i	Frequency of replacement

6.2.9 Rehabilitation (B5)

Rehabilitation involves major construction works aimed at extending the bridge's service life or improving its functionality. **Table 6-4** provides an example of LCI data required for this module.

Table 6-4: Examples of LCI data requirements for bridge rehabilitation (B5)

Rehabilitation Activity	Inventory Data	Parameter	Description
Seismic retrofitting	Reinforcement materials (FRP, steel), jacketing, anchoring, structural concrete	Seismic retrofitting	Reinforcement quantities (e.g., FRP, steel jacketing), and anchor systems
Full deck reconstruction	Demolition of old deck, new deck	Full deck replacement	Demolition of slab, falsework, new deck

[68] Environment Canada. (2015). Characterization and management of construction, renovation and demolition (CRD) waste in Canada – Final report. Government of Canada. https://publications.gc.ca/collections/collection_2025/eccc/En14-532-2015-eng.pdf

	materials, and traffic diversion impacts		materials, and traffic management
Barrier/drainage system upgrades	Replacement materials, installation tools, demolition waste	Drainage/safety upgrades	HDPE pipe lengths, barrier weights, anchor systems, and drainage mats

Seismic retrofitting may include installation of base-isolation systems, structural jacketing, FRP reinforcement, or anchoring systems.

Bridge widening represents an exceptional rehabilitation scenario. When widening increases the total deck area, practitioners should adjust the functional unit accordingly (e.g., emissions per square metre of deck area over the life cycle). Additional structural mass and associated material flows should be modelled explicitly.

6.2.9.1 *Data Collection*

- Derive frequency and scope from bridge design code, historic records, or engineering judgment.
- Model full-scale interventions such as deck reconstruction with corresponding demolition and replacement flows.
- Include temporary structures and detour impacts if significant.

Widening activities should be modelled as an incremental increase in structural mass per square meter of bridge deck. Emissions resulting from traffic disruptions or detours can be significant and should be assessed through scenario-based analysis.

6.2.9.2 *Emission Calculation*

Rehabilitation involves steps related to stage A1-A5 and related models for emission evaluation viewed in **Section 6.2.2- 6.2.4**

Operational Water (B7)

Regular watering of planted areas, especially during the establishment phase (typically 1–3 years post-installation). Water use may be estimated using:

- Metered water consumption data (if available)
- Irrigation schedules and system specifications (e.g., flow rate per emitter multiplied by runtime and frequency)
- Local climate data and evapotranspiration models to estimate irrigation demand

6.2.10 Deconstruction and Demolition (C1)

End-of-life stages represent the deconstruction and material management processes occurring when the bridge reaches the end of its service life. Module C1 includes the activities related to the mechanical or manual deconstruction of bridge components at the end of life.. Major mobilization activities at this stage relate to dismantling of bridge structure. Bridge demolition may require temporary support structures, traffic management, or closure of roadways or marine passages. These activities should be included in the operational inventory where relevant, including energy and emissions associated with temporary works and equipment used for traffic control. Similar process for the construction phase A5 LCI is followed in this module with the following considerations:

- Processes: Saw-cutting, jackhammering, crane-assisted lifting, torch cutting, demolition equipment operations.
- Inputs: Diesel or electricity used by demolition equipment (e.g., excavators, cranes, loaders).
- Outputs: Dust, noise, and direct emissions from fuel combustion (e.g., CO_2, NOx), water run-off should be accounted for when water sprays are used for dust suppression. This water may contain contaminants (e.g., particulate matter, chemical residues) and should be treated as an output stream with appropriate environmental impacts or disposal considerations.

6.2.10.1 *Data Collection*

Component Breakdown:

- Type and quantity of materials/components to be demolished (e.g., reinforced concrete deck, steel girders, asphalt surface).
- Surface area, thickness, and volume per component.

Demolition Method:

- Type of demolition (e.g., mechanical, manual, explosive-assisted).
- Equipment used (e.g., hydraulic breakers, jackhammers, excavators, cranes).

Operational Parameters:

- Equipment types
- Power rating of each equipment unit (hp or kW).
- Load factor (% of rated power used).
- Operating hours per unit of demolition activity.
- Fuel type and consumption rate (e.g., L/hr of diesel)
- Emission factors per equipment (kg CO_2/hp-hr or kg CO_2/kWh)

Site Factors:

- Location (urban/rural), space constraints, safety or traffic limitations.

6.2.10.2 *Emission Calculation*

- Quantify energy inputs based on equipment usage:

  $$\textit{Energy Use (MJ)=Power (kW)} \times \textit{Load Factor} \times \textit{Hours of Operation} \times 3.6$$

- Emissions from fuel combustion are calculated using region-specific emission factors:

  $$CO_2 \textit{ Emissions (kg)=Diesel Use (L)} \times 2.68 \textit{kg } CO_2/L$$

If multiple demolition stages are required (e.g., deck vs. substructure), analyze separately and sum flows.

6.2.11 Transport of Waste (C2)

Module C2 accounts for the transport of dismantled materials from the site to waste processing or disposal facilities. The data collection and analysis in this module should mirror the steps in **Section 5.2.3** Transport to Site (A4) of this guideline.

6.2.12 Waste Processing (C3)

Module C3 addresses energy and emissions from sorting, cleaning, shredding, or crushing of bridge materials prior to reuse, recycling, or disposal. When recycling occurs, recovered material flows may generate environmental benefits that are reported in Module D. The end-of-waste state is defined as the point at which materials leave the current system boundary, either through disposal or recovery for reuse/recycling. Recovered materials entering a new product life cycle should be modeled separately, practitioners should reference EN1580469 guidance on material recovery allocation.

6.2.12.1 *Data Collection*

Material Sorting and Processing:

- *Identify materials being processed (e.g., concrete, asphalt, steel).*
- *Weight or volume of material directed to processing.*

Processing Activities:

- *Type of process (e.g., crushing, shredding, cleaning, magnetic separation).*
- *Equipment and machinery specifications (power rating, throughput, fuel type).*
- *Energy source (diesel, electricity) and consumption per ton of material.*

Material Recovery Efficiency:

---

69 European Committee for Standardization. (2019). *EN 15804:2012 + A2:2019/AC:2021 — Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products*. BSI.

- *Recovery rates based on local facility or national statistics (e.g., 80% steel, 30% concrete).*

Losses and Residuals:

- *Percentage of material lost during processing.*
- *Dust, residue, and unusable fragments.*

6.2.12.2 *Emission Calculation*

- *Calculate energy inputs per unit material processed:*

$$Energy\ (MJ) = Equipment\ Power \times Time \times 3.6 \qquad \textbf{Equation 6.10}$$

- *Mass-based allocation of recycled content or waste streams (consider treatment of reused components or recovered materials)*
- *Model emissions based on:*
    - *Electricity grid intensity (kg CO_2/kWh)*
    - *Diesel consumption (L/ton) and fuel emission factors*
- *Apply recovery rates and report both recovered and residual material flows.*

6.2.13 Final Disposal (C4)

Module C4 includes landfilling, incineration, or any process where materials are permanently removed from the material cycle. Commonly disposed materials include coatings, insulation, contaminated concrete, asphalt binder residue. For each material stream, the end-of-life pathway should be specified. Options include reuse, recycling, energy recovery, or disposal. LCA Practitioners should document the chosen pathway, processing requirements, and any associated transport or treatment emissions to accurately model material flows.

6.2.13.1 *Data Collection*

Disposed Material Quantities:

- Identify material types and quantities not recovered (e.g., contaminated concrete, coatings, insulation).

Disposal Routes:

Specify the end-of-life pathway for each material type, including:

- Landfilling of mineral and inert materials (e.g., concrete, masonry)
- Incineration or hazardous waste treatment for reactive or potentially harmful materials (e.g., coatings, treated wood, lead-based paint)
- Specialized handling for asbestos or hazardous residues (if applicable)
- Destination type and distance from site (to support Module C2 where relevant).

Disposal Site Operations:

Document the use of landfill or incinerator equipment (e.g., compactors, bulldozers), including:

- Equipment types and fuel consumption
- On-site emission controls
- Leachate or landfill gas management systems (where relevant)

Waste Classifications:

Canada construction waste varies for federal, provincial and municipality level construction. Canada Environmental Protection Act (CEPA)[70] provides guidelines on handling, transportation and disposal of hazardous construction wastes related to federal projects. Some municipalities in Canada, such as City of Guelph[71] and district of Nanaimo[72], have construction waste management guides to develop diversion plans, material separation and minimum recycling rates that should be considered for stage C of bridge project.

- Materials should be identified based on their behavior in disposal:
    - Stable (inert) waste materials such as unpainted concrete and aggregate, which do not chemically react or biodegrade in landfills.
    - Reactive or degradable (non-inert) waste materials such as asphalt binder, painted surfaces, or insulation that may release emissions or degrade over time.
- Special handling or containment needs (if applicable)

6.2.13.2 *Emission Calculation*

- Use literature or regional data to estimate landfilling emissions (e.g., kg CO_2/ton for inert waste).
- Apply gas generation models for degradable or incinerated materials, where relevant.
- Treat hazardous materials per regulatory disposal requirements.
- Use standard fuel and emission factors if site-specific data are unavailable.
- Account for methane emissions from biodegradable waste.

  Include transport and on-site disposal emissions (e.g., compaction, capping, leachate control) if not covered in C2.

6.2.14 Beyond (D)

Module D represents potential environmental benefits or burdens associated with material recovery, recycling, or reuse occurring beyond the defined system boundary. For bridge infrastructure, common Module D benefits may include:

---

[70] Govt. of Canada (2021). Understanding the Canadian Environmental Protection Act. Canada.ca.

[71] Circular Opportunity Innovation Launchpad. (2024). Construction, renovation, and demolition waste management guidebook. Circular Innovation Council.

[72] Synergy Foundation. (2022, September). Construction waste best practices guide. Regional District of Nanaimo

- recycling of structural steel
- reuse of crushed concrete as aggregate
- material recovery from asphalt pavements

These benefits should be reported separately from the core life cycle results to avoid double counting.

Carbon sequestration potential of concrete depends on its composition and strength class. Recycled concrete aggregate (RCA) exhibits higher carbonation potential due to increased surface area exposure. Sequestration estimates should reflect these differences and be documented with assumptions regarding material type and exposure conditions. Carbon sequestration can be estimated using published sequestration rates by species and region (e.g., kg CO_2/year per tree or per square meter of green space). Tools such as i-Tree[73] or region-specific ecological models (see **Equation 5.8**[74]) can support this quantification. These estimates can be included as a negative emission (i.e., benefit) in the LCA model during the use stage, provided assumptions and sources are transparently documented.

$$Total\ CO2\ Impact\ (kg) = Sequestration - Decomposition$$

$$Total\ CO_2\ Impact\ (kg) = Years\ \times Quantity \times (EF_C\ \times (1 - N_D) + EF_D\ \times N_D)$$

Equation 6.11

Where:

Symbol	Description
$Quantity$	Number of the specified tree, with the adjustment of survival rate
EF	Net sequestration rate for median survival rate (kg CO2/year-tree) for coniferous (3.89) and deciduous trees (9.61), respectively
N	Fraction of planted trees that were deciduous. User-specified variable. Default = 0.5.

[73] I-Tree (2025). Tools for Assessing Individual Trees. https://www.itreetools.org/
[74] The Gold Standard Foundation. (2024). Methodology for Afforestation/Reforestation (A/R) GHGs Emission Reduction & Sequestration (Version 2.1). The Gold Standard Foundation. https://globalgoals.goldstandard.org/standards/403_V2.1_LUF_AR-Methodology-GHGs-emission-reduction-and-Sequestration-Methodology.pdf

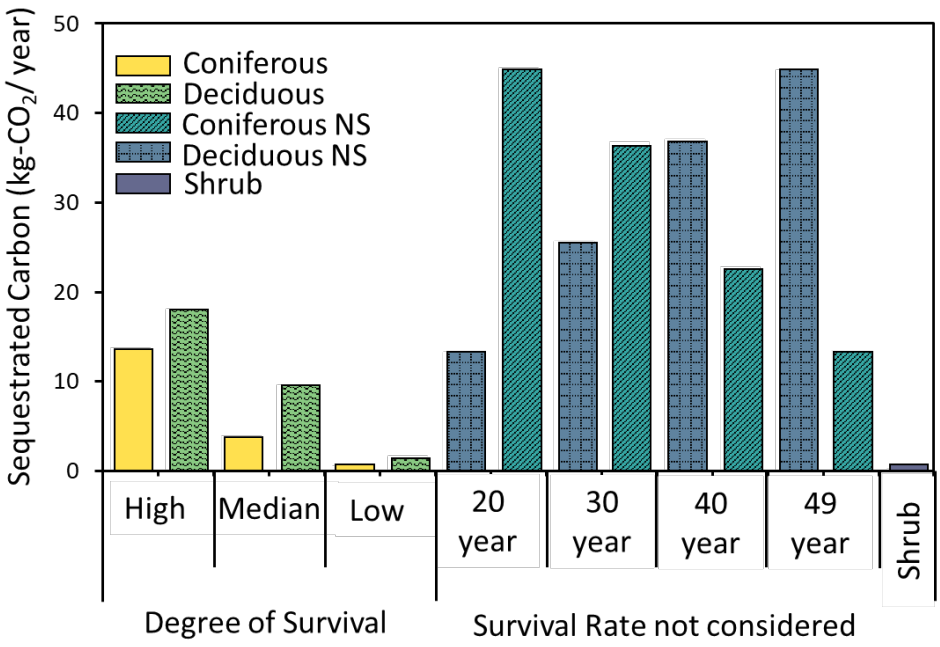


Figure 6-2:CO_2 Sequestrated by Trees Calculated for Different Tree Types and Period of Analysis

Where tree planting or vegetation is included for carbon sequestration, associated land-use change impacts (GWP) should be accounted for within the system boundary. Both sequestration benefits and potential emissions from land conversion should be included to avoid under- or overestimation of net carbon effects.

7. Interpretation

Life cycle interpretation is the fourth and final phase of the LCA study. ISO 14040 states that interpretation, "should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations". In this phase, the results of the inventory data and the environmental impacts are analysed to assess how well the LCA goal has been achieved. Interpreting results requires considering uncertainties, long-term implications, trade-offs, and selecting an appropriate functional unit to ensure meaningful and actionable insights. For bridge comparisons, the choice of materials, construction methods, data sources (primary and secondary), and maintenance plans can significantly affect the environmental impacts, and careful interpretation is needed to make informed decisions. **Figure 7-1** shows checkpoints in LCA study and how they relate with interpretation phase.

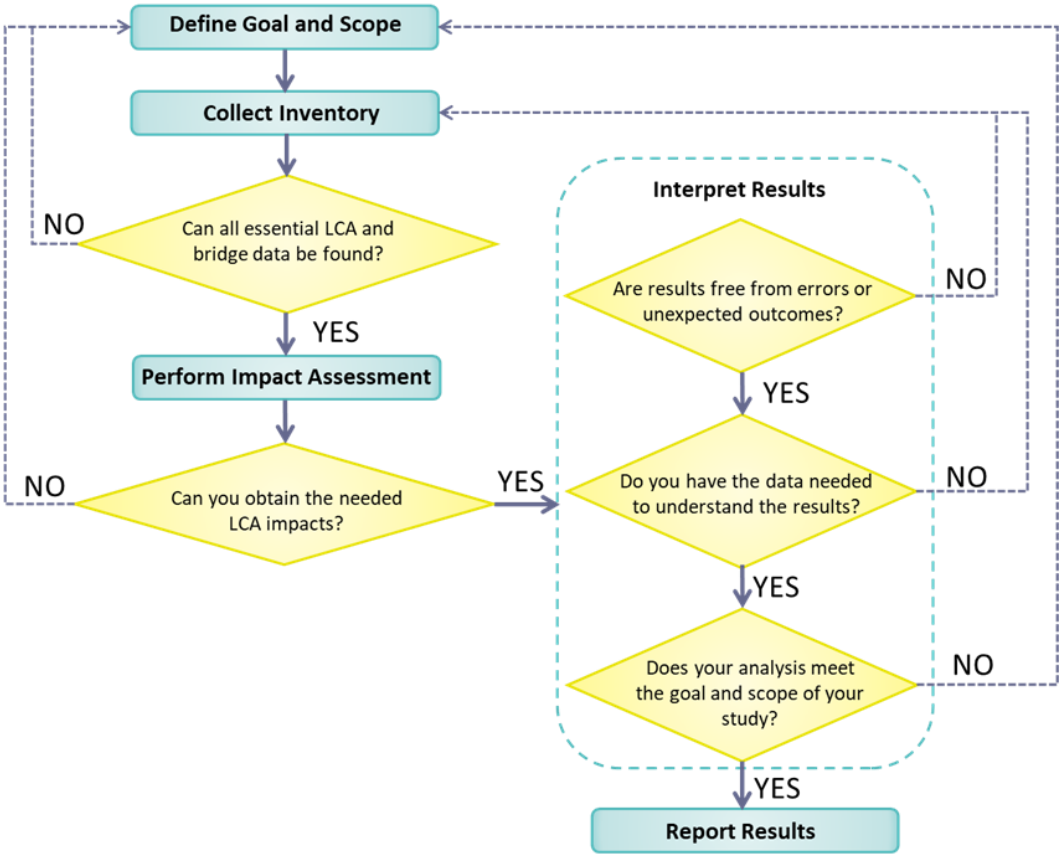


Figure 7-1: Checkpoints in LCA Study[75]

[1]

[75] Huang, M. Life Cycle Assessment of Buildings: A Practice Guide. The Carbon Leadership Forum, Department of Architecture, University of Washington (2018). Available at: http://hdl.handle.net/1773/41885

7.1 Key Factors for LCA Results Interpretation

The interpretation of LCI and LCIA results requires careful consideration of various factors to ensure accurate, meaningful conclusions:

- Sensitivity Analysis: The results should be interpreted with an understanding of the uncertainties and assumptions in data inputs. Sensitivity analyses may be performed to evaluate how key modelling assumptions influence the results. when comparing bridge design alternatives using the same design and service life, assumptions such as material quantities, maintenance frequency, or transport distance can be varied to evaluate their influence on life cycle emissions. While all alternatives must share consistent system boundaries and functional units, differences in service life between materials should also be considered, as one material-type of bridges may have longer lifespans than another material-type of bridge, influencing cumulative environmental impacts. For example, ultra-high-performance fibre-reinforced concrete (UHPFRC) may have a higher embodied carbon than conventional concrete, but if the bridge requires less material volume or structural mass, sensitivity analysis can show the net effect on overall GWP.
- Trade-offs and Evaluation Across Alternatives: When interpreting LCA results, all alternatives must be evaluated for the same analysis period, including replacement impacts for shorter-lived materials. Functional units should correspond to total bridge designs rather than generic per-area units. This ensures that comparisons are meaningful and reflect the total environmental impact over the life cycle. Problematic examples, such as referencing biodiversity or land use differences for specific materials without proper context, have been removed to maintain focus on consistent and comparable metrics.
- Long-Term Implications: The lifespan of a bridge is a crucial factor in interpreting LCA results. For example, while an initial material like steel may have a high environmental impact due to its production phase, its long lifespan, recyclability, and low maintenance costs may lead to a more favourable environmental impact over time, particularly when compared to materials with shorter lifespans like some plastics or composites.
- Functional Unit: The functional unit is defined in the Goal and Scope phase and is essential for meaningful comparisons. Functional units should reflect the total design case for a bridge and consider region, climate, performance standards, and bridge element type, ensuring that life cycle performance is accurately captured. Results are comparable when the same functional unit is applied across different bridge designs or materials in a Bridge LCA study.
- End-of-Life Considerations: It’s crucial to consider the impact of the bridge’s end-of-life phase when assessing different materials. For example, bridges made from timber or composite materials might have a higher cost or environmental impact when decommissioned or recycled, whereas steel and concrete might have established recycling or reuse systems that lower environmental impacts in this phase.
- Cumulative Impacts: The total impact of the bridge over its entire life cycle must be considered. For instance, a steel bridge may have a higher environmental impact during construction but lower maintenance needs during operation than a concrete bridge.

Depending on the service life, this longer operational phase could lead to a lower overall impact.

- Data Quality and Comparability: The quality of LCI data influences the interpretation of results. For example, if LCA studies use different assumptions about the origin of materials, the energy mix used in construction, or transportation distances, the results may not be directly comparable. Understanding these assumptions is crucial for drawing valid comparisons.

7.2 Uncertainty and Sensitivity Analysis

Uncertainty and sensitivity analysis are critical components of a robust LCA for bridges and often considered as complementary components of a robust LCA study,, ensuring that decision-makers understand the reliability of the results and the influence of key assumptions. Given the complex nature of bridge infrastructure, with long service lives, variable maintenance schedules, and diverse environmental exposures, incorporating uncertainty analysis becomes essential as it helps quantify the range of possible outcomes due to data variability or gaps. On the other hand, sensitivity analysis identifies which input parameters most significantly impact the results, guiding future data collection and decision priorities.

7.2.1 Uncertainty analysis

Uncertainty analysis quantifies the influence of variability in input data, model assumptions, and key methodological choices on LCA results. At interpretation phase the ambiguous categories such as “choices and future physical systems” have been clarified to focus on the aspects that can influence the reliability of results, including methodological assumptions, parameter values, and scenario choices ISO 14040/14044 recommends using uncertainty analysis to increase reliability of LCA results. The main goal of uncertainty analysis is to assess how uncertain input data impacts the LCA results. Sources of uncertainty can be the material quantities, impact coefficients, material waste rates, material density, temporal, spatial variations, system boundaries, maintenance and replacement processes and others. The uncertainty related to LCI data quality can be interpretated through conversion of pedigree scores of DQA (Chapter 4) into uncertainty scores used in Monte Carlo simulation. **Figure 7-2** shows a simplified representation of how the uncertainty is translated from DQA to results.

Zhang et al. (2016)[76] evaluated endpoint and single score impacts uncertainty for a bridge located in Shanxi, China. About 8000 Monte Carlo simulations were conducted to assess the distribution of these impacts. The statistical characteristics obtained for these impacts during the bridge life cycle are shown in **Table 7-1** and the related distribution curves are shown **iFigure 7-2.** It is evident that the distribution varies with the type of processes and the type of environmental impact.

[76] Zhang, Y. R., Wu, W. J., & Wang, Y. F. (2016). Bridge Life Cycle Assessment with data uncertainty. *The International Journal of Life Cycle Assessment*, *21*, 569-576. https://doi.org/10.1007/s11367-016-1035-7

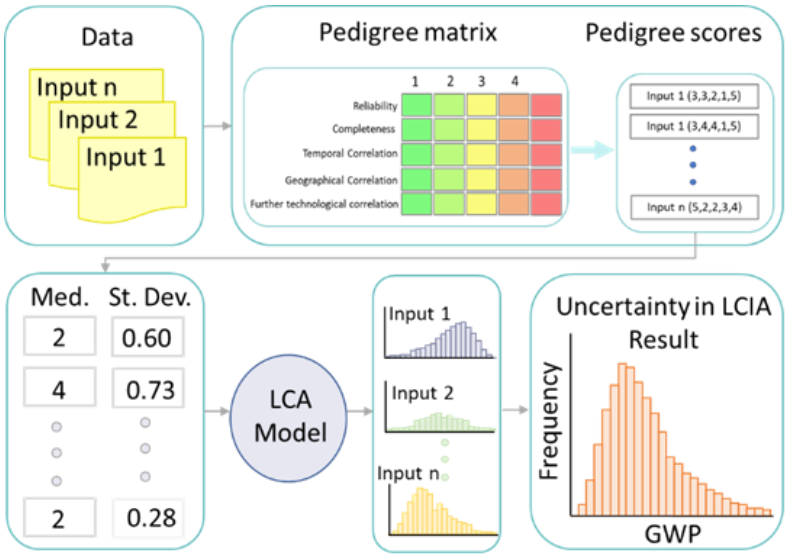


Figure 7-2: Schematic showing uncertainty propagation using DQA

Table 7-1: Statistical characteristics of weighted value of LCA impacts[77]

Impact Category		Human health damage	Ecological system damage	Resource and energy consumption
Raw materials acquire and process	μ	379.2	79.4	1036.1
	σ	151.1	26.2	62.9
	COV	39.84%	33.04%	6.07%
Construction	μ	55	30	30
	σ	86.4	53.7	28.8
	COV	38.85	45.12	6.26
Operation	μ	1084.6	1600.4	547.2
	σ	434.1	589.5	29.9
	COV	40.02%	36.84%	5.47%
Final disposal	μ	7.2	9.8	40.7
	σ	2.8	4.2	2.4
	COV	39.13%	43.26%	5.99%

[77] Zhang, Y. R., Wu, W. J., & Wang, Y. F. (2016). Bridge life cycle assessment with data uncertainty. *The International Journal of Life Cycle Assessment*, *21*, 569-576. https://doi.org/10.1007/s11367-016-1035-7

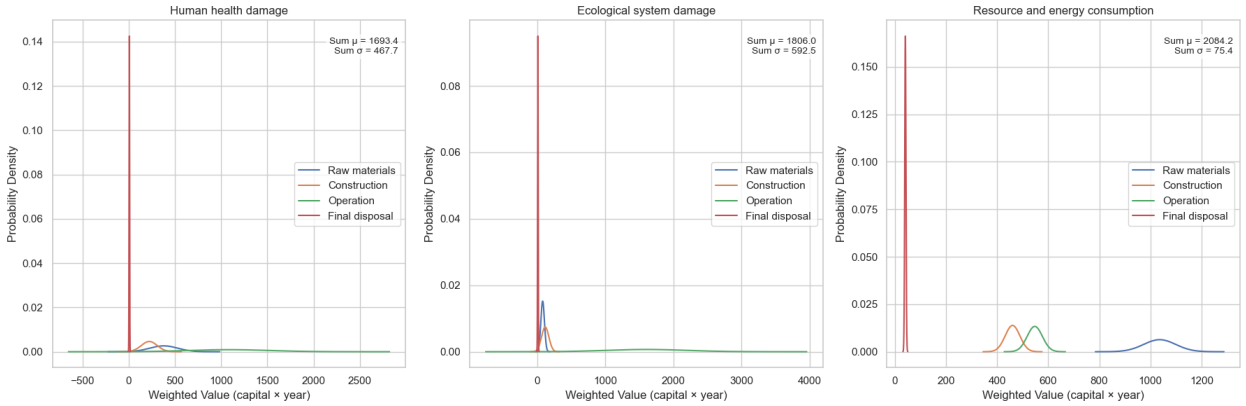


Figure 7-1: Distribution curves based on Zhang et al. (2016)[92]

It is evident that the distribution varies with the type of processes and the type of environmental impact.

7.2.2 Sensitivity Analysis

Sensitivity analysis systematically evaluates how assumptions and methodological choices affect study outcomes. This is distinct from contribution analysis, which identifies which flows or processes contribute most to overall impacts. Both analyses are important for interpretation: contribution analysis highlights influential inputs, while sensitivity analysis tests how changes in assumptions such as service life, material quantity, or transport distance affect results. Following FHWA guidance, sensitivity analysis can consider parameters such as:

- Material production and composition (type, quantity, sourcing, manufacturing),
- Construction and maintenance activities (techniques, energy use, maintenance frequency),
- Traffic characteristics (vehicle types, volumes, loading),
- Environmental conditions (temperature, precipitation, de-icing chemicals), and
- End-of-life scenarios (demolition, recycling, disposal, reuse potential).

Systematically testing these parameters ensures that decision-makers understand which assumptions have the greatest impact on LCA outcomes and helps prioritize data collection for future studies. Another goal is to identify most influential parameters that need to be investigated for uncertainty assessment.

There are two types of sensitivity analysis methods used in LCA: local sensitivity analysis and global sensitivity analysis[78]. Pearson correlation and Spearman correlation coefficient analysis are two most common techniques used for sensitivity analysis. Zhang et al. (2016)[57] evaluated sensitivity analysis of different substances on the three endpoint impacts (**Table 7-2**). The impacts

[78] Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., & Mathias, J. D. (2015). How to conduct a proper sensitivity analysis in Life Cycle Assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. *Environmental science & technology*, *49*(1), 377-385. https://doi.org/10.1021/es502128k

are sensitive to different materials for instance in this example, PM10 is most important for human heath while NOX change will be most relevant for ecological system damage.

Table 7-2: Sensitivity of different pollutant discharges on LCA impacts[79]

Substance	Human health damage (%)	Ecological system damage (%)	Resource and energy consumption (%)
CO2	0.04		
CH4	0.74		
N2O	11.62		
VOC	0.11		
NOX	15.01	84.6	
PM10	63.16		
CO	15.01		
SOX	9.20	15.4	
Limestone			0.4
Fe			0.9
Mn			5.4
Coal			35.0
Oil			58.4

[79] Zhang, Y. R., Wu, W. J., & Wang, Y. F. (2016). Bridge life cycle assessment with data uncertainty. *The International Journal of Life Cycle Assessment*, *21*, 569-576. https://doi.org/10.1007/s11367-016-1035-7

8. Reporting

This section outlines recommended practices for presenting LCIA outcomes in a clear, consistent, and accessible manner. Effective communication of LCIA results is essential to support decision-making, promote transparency, and engage stakeholders throughout the infrastructure life cycle

8.1 Presentation of Results

- Present results by life cycle stage (A–C) and by impact category (e.g., Global Warming Potential, Acidification, Resource Use). Where useful, results may also be summarized by major inventory flows (e.g., fuel consumption, material quantities) to illustrate the key drivers of environmental impacts. Further breakdown of the stages may be required when embodied carbon is of interest, such as stage A (A1-A3); stage B (B1-B5) and stage C (C1-C4). When operational carbon is part of study goal and scope, impacts pertaining to B6 will be shown separately.
- Use tables, bar charts, and Sankey diagrams to visually communicate key processes and materials' contributions.
- Highlight hotspots (e.g., high-emission activities such as deck replacement or material transport) to aid in the prioritization of mitigation efforts.
- Provide results relative to the defined functional unit (e.g., kg CO_2e per m² of deck area over the reference service life). Normalized metrics should only be used when projects share equivalent functional units, service life assumptions, and performance requirements to avoid misleading comparisons.

8.2 Summary and Interpretation

- Summarize key findings in relation to the defined functional unit and analysis period. Where comparisons are made between bridge alternatives, the analysis period should be consistent across options and reflect the reference service life and maintenance schedule of the structur.
- Include brief narrative explanations to contextualize numerical results, supported by sensitivity or scenario analysis where applicable.
- State methodological choices (e.g., system boundaries, allocation methods, impact assessment models) that influence interpretation.

8.3 Transparency and Stakeholder Communication

- Ensure that all assumptions, data sources, and uncertainties are disclosed or referenced.
- Tailor communication for different audiences:
    - Technical stakeholders (e.g., engineers and LCA practitioners) require detailed breakdowns and data transparency.
    - Non-technical stakeholders (e.g., policymakers and the public) benefit from summaries, visuals, and plain-language explanations.

- Use scenario comparisons (e.g., baseline vs. rehabilitation strategy) to support sustainable decision-making.

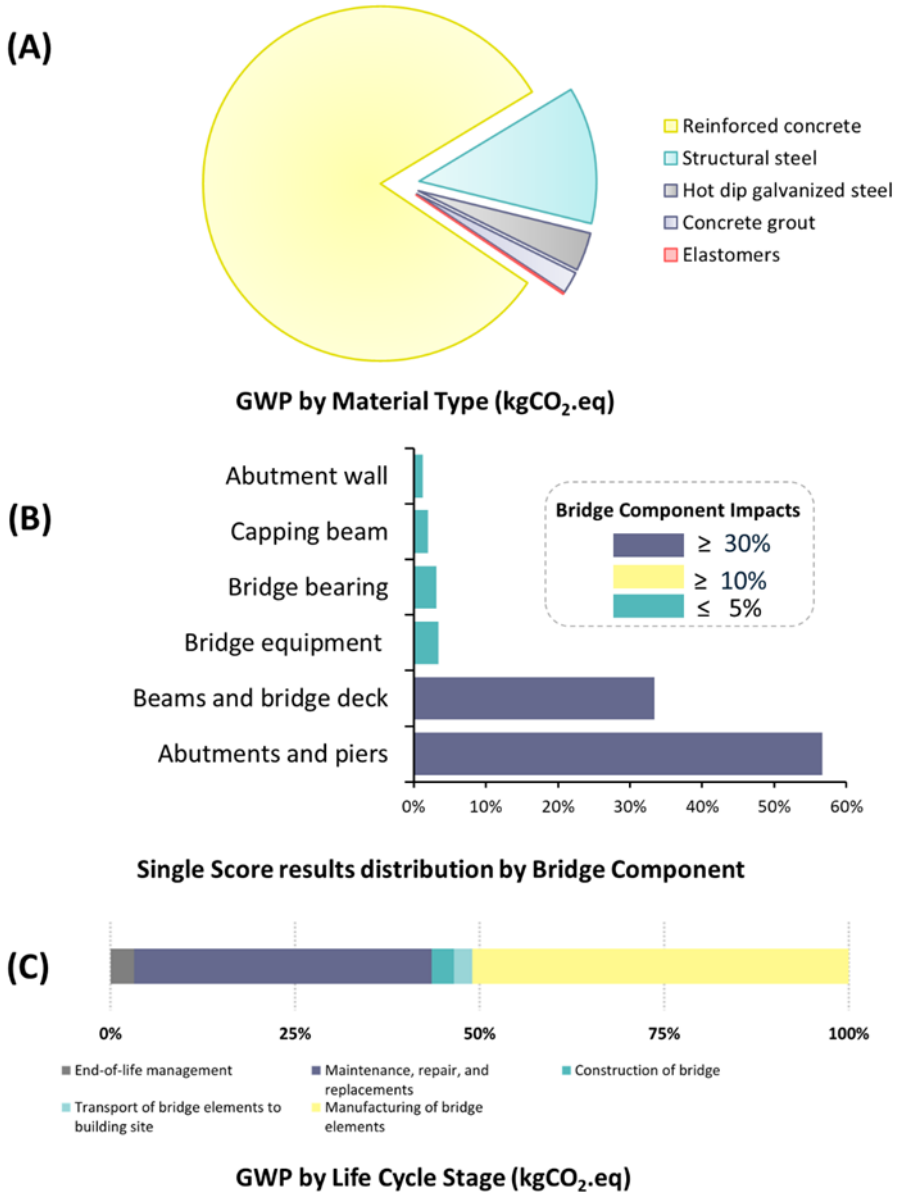


Figure 8-1: Example illustration for LCA results of bridge[80],[81],[82]

[80] Dumoulin, J. et al. Comparative life cycle assessment of resource road bridges. FPInnovations Technical Report No. TR2020N51, Project Number: 301014016 (2020). Available at: https://library.fpinnovations.ca/media/FOP/TR2020N51.PDF
[81] Mitterpach, J., Fojtík, R., Machovčáková, E. & Kubíncová, L. Life cycle assessment of a road transverse prestressed wooden–concrete bridge. Forests 14, 16 (2022). https://doi.org/10.3390/f14010016
[82] Zero Emissions Building Exchange. (2021). Life cycle assessment practice to estimate embodied carbon in buildings (Net-Zero Energy-Ready Playbook Series). https://www.zebx.org/wp-content/uploads/2021/06/Embodied-Carbon-Playbook-June-21.pdf

Reference

All Annex I Parties, excluding the US, have participated in the 1st Kyoto commitment period. 37 Annex I countries and the EU have agreed to second-round Kyoto targets.

Arvanitoyannis, I. S. (2008). ISO 14040: life cycle assessment (LCA)–principles and guidelines. Waste management for the food industries (pp. 97-132). ISBN: 9780123736543

Barandica, J. M., Fernández-Sánchez, G., Berzosa, Á., Delgado, J. A., & Acosta, F. J. (2013). Applying life cycle thinking to reduce greenhouse gas emissions from road projects. Journal of cleaner production, 57, 79-91. https://doi.org/10.1016/j.jclepro.2013.05.036

Bowick, M., O'Connor, J., Salazar, J., Meil, J., & Cooney, R. (2022). National guidelines for whole-building life cycle assessment. Ottawa: National Research Council Canada. https://doi.org/10.4224/4000274

BSI. (2022). BS EN 17472: 2022. Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods.

Canadian Construction Association. (2024). Quarterly insights report Q4 2023: The construction industry and greenhouse gas emissions (p. 8). Canadian Construction Association. https://www.cca-acc.com/wp-content/uploads/2024/04/ICIC-Quarterly-insights-Q4-2023.pdf

Cement Association of Canada. (2021). How cement and concrete are made. https://cement.ca/the-cement-and-concrete-industry/how-cement-and-concrete-are-made/

Chen, X., Shi, P., & Wang, H. (2025). Life cycle environmental impact assessment of bridges based on comparison of different construction schemes. *Environment, Development and Sustainability*, 1-33. https://doi.org/10.1007/s10668-024-05895-6

Cherubini, F., Strømman, A. H., & Ulgiati, S. (2011). Influence of allocation methods on the environmental performance of biorefinery products—A case study. Resources, Conservation and Recycling, 55(11), 1070-1077. https://doi.org/10.1016/j.resconrec.2011.06.001

Circular Opportunity Innovation Launchpad. (2024). Construction, renovation, and demolition waste management guidebook. Circular Innovation Council.

CSA S6:19 (2019). Canadian Highway Bridge Design Code. Canadian Standards Association Group.

Deschamps, J., Tagnit-Hamou, A., Fournier, B., & Amor, B. (2021). Assessing the Environmental Benefits of Using Glass Powder as a Supplementary Cementitious Material in a Context of Open-loop Recycling.

Dong, Y., Hossain, M. U., Li, H., & Liu, P. (2021). Developing conversion factors of LCIA methods for comparison of LCA results in the construction sector. *Sustainability*, *13*(16), 9016. https://doi.org/10.3390/su13169016

Du, G., & Karoumi, R. (2013). Life Cycle Assessment of a railway bridge: comparison of two superstructure designs. *Structure and Infrastructure Engineering*, *9*(11), 1149-1160. https://doi.org/10.1080/15732479.2012.670250

Du, G., & Karoumi, R. (2014). Life Cycle Assessment framework for railway bridges: literature survey and critical issues. Structure and Infrastructure Engineering, 10(3), 277-294. https://doi.org/10.1080/15732479.2012.749289

Dumoulin, J. et al. Comparative life cycle assessment of resource road bridges. FPInnovations Technical Report No. TR2020N51, Project Number: 301014016 (2020). Available at: https://library.fpinnovations.ca/media/FOP/TR2020N51.PDF

Ecoinvent ecoinvent - Data with purpose.

Environment and Climate Change Canada (ECCC) (2016). Pan-Canadian Framework on Clean Growth and Climate Change: Canada's plan to address climate change and grow the economy. ISBN 978-0-660-07023-0

Environment and Climate Change Canada (ECCC) (2025) https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/sources-sinks-executive-summary-2025.html

Environment and Climate Change Canada (ECCC) (2025). Reporting greenhouse gas emissions data: technical guidance - Canada.ca

Environment and Climate Change Canada (ECCC). (2025). National inventory report 1990–2023: Greenhouse gas sources and sinks in Canada. Part 3: Annexes 8 to 13. Government of Canada. https://publications.gc.ca/site/eng/9.506002/publication.html

Environment and Climate Change Canada ECCC (2024). Fuel Life Cycle Assessment Model User Manual. Gatineau Quebec. https://publications.gc.ca/collections/collection_2024/eccc/en4/En4-418-3-2024-eng.pdf

Environment Canada and Climate Change (ECCC) (2016). Canadian Environmental Sustainability Indicators: Greenhouse Gas Emissions.

Environment Canada. (2015). Characterization and management of construction, renovation and demolition (CRD) waste in Canada – Final report. Government of Canada. https://publications.gc.ca/collections/collection_2025/eccc/En14-532-2015-eng.pdf

Eriksen, J., Gervasio, H., Rebelo, C., Silva, L. S. D., Veljkovic, M., & Vesikari, E. (2008). Guidelines to perform life cycle analysis of bridges. In COST Action C25 Seminar on Sustainability of Constructions-Integrated approach to life-time structural engineering: 06/10/2008-07/10/2008 (pp. 5-27).

European Committee for Standardization. (2019). *EN 15804:2012 + A2:2019/AC:2021 — Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products*. BSI.

Fernández-Sánchez G, Berzosa Á, Barandica JM, Cornejo E, Serrano JM. (2015). Opportunities for GHG emissions reduction in road projects: a comparative evaluation of emissions scenarios using CO2NSTRUCT. Journal of Cleaner Production.104:156-67. https://doi.org/10.1016/j.jclepro.2015.05.032

Fuel Efficiency Benchmarking in Canada's Trucking Industry - Natural Resources Canada

Gervásio, H., da Silva, L. S., Perdigão, V., Orcesi, A., & Andersen, R. (2015). Influence of maintenance strategies on the life cycle performance of composite highway bridges. Structural Engineering International, 25(2), 184-196. https://doi.org/10.2749/101686614X14043795569978

GHG Protocol tools Calculation Tools and Guidance | GHG Protocol and Corporate Value Chain (Scope 3) Standard | GHG Protocol

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., & Zelm, R. v. (2009). ReCiPe 2008-A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Holland

Govt. of Canada (2021). Understanding the Canadian Environmental Protection Act. Canada.ca.

GreenDelta. Data quality - openLCA 2 manual. https://greendelta.github.io/openLCA2-manual/advanced_top/data_quality.html

Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., & Kendall, A. (2016). Pavement Life Cycle Assessment framework (No. FHWA-HIF-16-014). United States. Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/38470/dot_38470_DS1.pdf

Horvath, A. (2009). Principles of using life-cycle assessment in bridge analysis. In Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials, Sapporo, Japan, October (pp. 21-22).

Hu, S., Ma, W., Zhu, Y., & Cong, L. (2023). Research on Information Coding and Management for Big Data Mining in Highway Bridge Operation and Maintenance. In 2023 3rd International Conference on Public

Management and Intelligent Society (PMIS 2023) (pp. 1090-1097). Atlantis Press. https://doi.org/10.2991/978-94-6463-200-2_115

Huang, M. Life Cycle Assessment of Buildings: A Practice Guide. The Carbon Leadership Forum, Department of Architecture, University of Washington (2018). Available at: http://hdl.handle.net/1773/41885

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A.Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The international journal of Life Cycle Assessment, 22, 138-147. https://doi.org/10.1007/s11367-016-1246-y

ILCD Handbook Draft recommended LCIA methods

IMPACT World+

Intergovernmental Panel on Climate Change. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

International Organization for Standardization. (2017). ISO 21930:2017 Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services. ISO.

Inti, S., Sharma, M., & Tandon, V. (2016). An approach for performing Life Cycle Impact Assessment of pavements for evaluating alternative pavement designs. Procedia Engineering, 145, 964-971. https://doi.org/10.1016/j.proeng.2016.04.125

ISO (2006a). ISO 14040 International Standard. In: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organisation for Standardization, Geneva, Switzerland. ISO, 2006b. http://www.iso.org/iso/catalogue_detail?csnumber=37456

ISO (2006b) ISO 14044 International Standard. In: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland. http://www.iso.org/iso/catalogue_detail?csnumber=38498

ISO 21930:2017 - Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services

I-Tree (2025). Tools for Assessing Individual Trees. https://www.itreetools.org/

Jalaei, F., Zhang, J., Mcneil-Ayuk, N., & McLeod, C. (2025). Environmental Life Cycle Assessment (LCA) for design of climate-resilient bridges–a comprehensive review and a case study. International Journal of Construction Management, 25(1), 99-114. https://doi.org/10.1080/15623599.2024.2304479

Mahajan, G. R., Radhika, B., & Biligiri, K. P. (2022). A critical review of vehicle-pavement interaction mechanism in evaluating flexible pavement performance characteristics. Road Materials and Pavement Design, 23(4), 735-769. https://doi.org/10.1080/14680629.2020.1860806

Malzer, J. L. (2005). Aspects of energy use and emissions by heavy trucks (Master's thesis, University of Manitoba).

Mattinzioli, T., Butt, A. A., & Harvey, J. (2023). Literature review on pavements and electric vehicle interaction: A research roadmap. Transportation Research Part D: Transport and Environment, 122, 103886. https://doi.org/10.1016/j.trd.2023.103886

Min, Q. (2020). Quantifying greenhouse gas mitigation measures during provincial highway design, construction, and maintenance activities (Master's thesis, University of Waterloo). http://hdl.handle.net/10012/16577

Mitterpach, J., Fojtík, R., Machovčáková, E. & Kubíncová, L. Life cycle assessment of a road transverse prestressed wooden–concrete bridge. Forests 14, 16 (2022). https://doi.org/10.3390/f14010016

MOVES Nonroad Technical Reports | US EPA

National Academies of Sciences, Engineering, and Medicine (2013). Fuel Usage Factors in Highway and Bridge Construction. Washington, DC: The National Academies Press. https://doi.org/10.17226/22629

National Inventory Report En81-4-2020-2-eng.pdf

National inventory report: greenhouse gas sources and sinks in Canada National inventory report : greenhouse gas sources and sinks in Canada.: En81-4E-PDF - Government of Canada Publications - Canada.ca

Nicholson, A. L., Olivetti, E. A., Gregory, J. R., Field, F. R., & Kirchain, R. E. (2009, May). End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. In 2009 IEEE international symposium on sustainable systems and technology (pp. 1-6). IEEE. https://doi.org/10.1109/ISSST.2009.5156769

NRC (2014) Auto$mart - Learn the facts: Emissions from your vehicle (Factsheet 9). Office of Energy Efficiency

PaLATE - Pavement Life-cycle Tool

Pavement LCA | Life Cycle Assessment Software

Pavements - Federal Highway Administration

Prado, V., Rogers, K., & Seager, T. P. (2012). Integration of MCDA tools in valuation of comparative Life Cycle Assessment. Life Cycle Assessment handbook: A guide for environmentally sustainable products, 413-432.

Qin, Y., Cucurachi, S., & Suh, S. (2020). Perceived uncertainties of characterization in LCA: a survey. *The International Journal of Life Cycle Assessment*, *25*, 1846-1858. https://doi.org/10.1007/s11367-020-01787-9

Railway Association of Canada Locomotive Emissions Monitoring Program 2015-LEM-Report.pdf

Ramirez, A.R., Khamlichi, A. E., Markowz, G., Rettenmaier, N., Baitz, M., Jungmeier, G., Bradley, T. (2020). LCA4CCU Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation. https://doi.org/10.2833/161308

RICS (2023) Whole Life Carbon Assessment for the Built Environment, RICS Professional Standard, 2nd edition, Whole Life Carbon Assessment for the Built Environment, RICS Professional Standard, 2nd edition - RICS iConsult. https://consultations.rics.org/whole_life_carbon_standard/viewCompoundDoc?docid=13626324&partId=13629428.

Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy, 16, 329-339. https://doi.org/10.1007/s10098-013-0629-z

Santos, J., Miller, S. R., & Cerezo, V. (2022, November). Pavement vehicle interaction (PVI): the elephant in the pavement Life Cycle Assessment (LCA) room. In CROW Infradagen 2022.

Statistics Canada. (2022, May 24). Canada's Core Public Infrastructure Survey: Roads, bridges and tunnels, 2020. Government of Canada. https://www150.statcan.gc.ca/n1/daily-quotidien/220524/dq220524a-eng.htm

Suh, S.; Weidema, B.; Schmidt, J.H.; Heijungs, R. Generalized Make and Use Framework for Allocation in Life Cycle Assessment. J. Ind. Ecol. 2010, 14, 335–353.

Synergy Foundation. (2022, September). Construction waste best practices guide. Regional District of Nanaimo

The Gold Standard Foundation. (2024). Methodology for Afforestation/Reforestation (A/R) GHGs Emission Reduction & Sequestration (Version 2.1). The Gold Standard Foundation. https://globalgoals.goldstandard.org/standards/403_V2.1_LUF_AR-Methodology-GHGs-emission-reduction-and-Sequestration-Methodology.pdf

TRACI Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) | US EPA

U.S. Environmental Protection Agency, Office of Chemical Safety and Pollution Prevention. (2024). *A vision and plan to improve secondary life cycle assessment data used in environmental product declarations*. U.S. Environmental Protection Agency.

U.S. Life Cycle Inventory Database U.S. Life Cycle Inventory Database | Energy Analysis | NREL

United States of America Environmental Protection Agency (US EPA) GHG Emission Factors Hub | US EPA

Van Dam, T. J., J. T. Harvey, S. T. Muench, K. D. Smith, M. B. Snyder, I. L. Al-Qadi, H. Ozer, J. Meijer, P. V. Ram, J. R. Roesler, and A. Kendall. (2015). Towards Sustainable Pavement Systems: A Reference Document. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC

Venfitti, R.A. (2016) Lecture 14: Normalization, Weighting and Aggregation to Single Score Environmental Life Cycle Assessment PSE 476/FB 576

Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., & Mathias, J. D. (2015). How to conduct a proper sensitivity analysis in Life Cycle Assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. *Environmental science & technology*, *49*(1), 377-385. https://doi.org/10.1021/es502128k

Worldsteel Association. The steel making process. https://worldsteel.org/wp-content/uploads/steelmaking-process.pdf

Zero Emissions Building Exchange. (2021). Life cycle assessment practice to estimate embodied carbon in buildings (Net-Zero Energy-Ready Playbook Series). https://www.zebx.org/wp-content/uploads/2021/06/Embodied-Carbon-Playbook-June-21.pdf

Zhang, Y. R., Wu, W. J., & Wang, Y. F. (2016). Bridge Life Cycle Assessment with data uncertainty. *The International Journal of Life Cycle Assessment*, *21*, 569-576. https://doi.org/10.1007/s11367-016-1035-7

9. Appendices

9.1 Appendix A: Bridge Life Cycle Inventory Data

Table 9-1: Bridge life cycle inventory data

Data Type	Sub type	Source
Primary data Sources	Project-Specific Data	• Bill of materials • Construction drawings and specifications • Description of construction processes • Service life of the structure • Maintenance plan • End-of-life plan • Cost of materials, construction processes (equipment, labour, etc.), maintenance and demolition • Records of construction processes, equipment, and energy use
	Product specific data	• Third-party verified EPDs
	Environmental and Operational Data	• Traffic data • Service life estimates • Local environmental conditions
Secondary Sources	LCI Databases	• Ecoinvent • GaBi • DATASMART • U.S. LCI Database
	Published Literature and Reports	• Previous LCA studies • Technical reports from research institutes or government agencies • These sources can offer benchmark data or validated inventory information for similar bridge types or materials

9.2 Appendix B: Dataset for Bridge LCI

Fuel related carbon emissions can be estimated using Fuel LCA Model developed for Canada[83]. The fuel usage factors presented in Table 9-2 represent construction equipment fuel consumption associated with on-site construction activities, including material placement, excavation, and equipment operation. These values represent historical benchmarks and should be updated with project-specific or modern equipment fuel efficiency data where available. These values do not include upstream manufacturing energy for construction materials, which should be accounted for separately using LCI datasets or Environmental Product Declarations (EPDs).

Table 9-2: Indicative Fuel usage factors in highway and bridge construction –Adapted from NCHRP Report 744[84]

Category	Item of Work	Units	FUF	1980 FUF
Clearing and Removal	Clearing	Litre /hectare	1,787.72	1,870
	Pipe Removal	Litre /m	10.70	
	Pavement Removal - Asphalt	Litre/m^3	6.92	
	Pavement Removal - Concrete	Litre/m^3	2.78	
	Structure Demolition (House/Building)	Litre /Each	1,419.53	
	Structure Demolition (Bridge per S.F. of Deck)	Litre/m^2	25.51	
Excavation	Excavation - Earth - Off Road - Long Haul	Litre/m^3	1.58	2.18
	Excavation - Earth - Off Road - Short Haul	Litre/m^3	1.30	
	Excavation - Earth - On Road - Long Haul	Litre/m^3	3.40	
	Excavation - Earth - On Road - Short Haul	Litre/m^3	1.58	
	Excavation - Rock - Off Road - Long Haul	Litre/m^3	1.99	2.82
	Excavation - Rock - Off Road - Short Haul	Litre/m^3	1.54	
	Excavation - Rock - On Road - Long Haul	Litre/m^3	3.66	
	Excavation - Rock - On Road - Short Haul	Litre/m^3	2.30	
	Strip Topsoil	Litre/m^3	0.83	
	Roadway Finishing	Litre/m^2	0.33	

[83] Environment and Climate Change Canada ECCC (2024). Fuel Life Cycle Assessment Model User Manual. Gatineau Quebec. https://publications.gc.ca/collections/collection_2024/eccc/en4/En4-418-3-2024-eng.pdf
[84] National Academies of Sciences, Engineering, and Medicine (2013). Fuel Usage Factors in Highway and Bridge Construction. Washington, DC: The National Academies Press. https://doi.org/10.17226/22629

Base Stone	Base Stone - Short Haul (Haul and Place)	Litre/ton	1.69	2.13
	Base Stone - Long Haul (Haul and Place)	Litre/ton	2.33	3.38
Asphalt	Asphalt Production (Diesel)	Litre/ton	8.51	10.72
	Asphalt Production (Natural Gas)	Litre (GGE)/ton	8.94	
	Asphalt Production (Natural Gas) (Support Equipment)	Litre/ton	0.38	
	Warm Mix Asphalt Production (Diesel)	Litre/ton	6.81	
	Warm Mix Asphalt Production (Natural Gas)	Litre (GGE)/ton	7.15	
	Warm Mix Asphalt Production (Natural Gas) (Support Eqp.)	Litre/ton	0.30	
	Asphalt Hauling (0-5 miles)	Litre/ton	0.76	3.21
	Asphalt Hauling (6-15 miles)	Litre/ton	1.22	
	Asphalt Hauling (>15 miles)	Litre/ton	2.14	4.47
	Asphalt Placement	Litre/ton	1.14	1.17
Milling	Milling - 0-1" (0-5 mile haul)	Litre/ton	0.12	
	Milling - 0-1" (6-15 mile haul)	Litre/ton	0.13	
	Milling - 0-1" (>15 mile haul)	Litre/ton	0.16	
	Milling - 2-4" (0-5 mile haul)	Litre/ton	0.26	
	Milling - 2-4" (6-15 mile haul)	Litre/ton	0.30	
	Milling - 2-4" (>15 mile haul)	Litre/ton	0.38	
Structures	Reinforcing Steel	Litre/kg	0.03	
	Steel Beams	Litre/m	2.23	
	Substructure Concrete	Litre/m^3	23.27	
	Superstructure Concrete	Litre/m^3	20.54	
	Bridges	Litre/$	19.68	155.19
	Bridges (per S.F. of deck)	Litre/m^2	25.10	
	Concrete Production (Support Equipment)	Litre/m^3	0.45	2.13
	Concrete Hauling - Short Haul	Litre/m^3	2.97	4.95

Misc. Concrete	Concrete Hauling - Long Haul	Litre/m^3	5.45	4.95
	Concrete Placement	Litre/m^3	1.32	2.33
	Concrete Curb/Gutter	Litre/m	1.88	
	Concrete Sidewalk	Litre/m^2	3.67	
	Retaining Wall (Cast in Place)	Litre/m^2	26.32	
	Noise Wall (Pre-Cast)	Litre /m^2	12.39	
	Concrete Median Barrier	Litre/m	3.83	3.72
Drainage Pipe and Structures	Large Pipe Crew	Litre/m	53.79	
	Medium Pipe Crew	Litre/m	18.36	
	Small Pipe Crew	Litre/m	10.80	
	Drainage Structures	Litre/Each	99.08	
Specialty Items	Fence Gates	Litre/Each	15.90	
	Fencing	Litre/m	0.53	
	Grassing (Hydro Seeding)	Litre /hectare	32.70	
	Grassing (Seedbed Preparation)	Litre /hectare	93.50	
	Sodding	Litre/m^2	0.08	
	Guardrail Posts	Litre/Each	0.16	
	Guardrail - Steel	Litre/m	0.46	2.85
	Guardrail - Wire/Cable	Litre/m	1.30	
	Intersection Signalization (2 Lane)	Litre/Each	643.52	
	Intersection Signalization (4 Lane)	Litre/Each	1,150.76	
	Pavement Marking	Litre/km	47.66	

9.3 Appendix C: Sample Calculations

The subsections in this section serve different purposes in supporting bridge Life Cycle Assessment (LCA) implementation. Section 9.1 provides illustrative examples of typical bridge life cycle inventory (LCI) data sources. Section 9.2 presents recommended default datasets and parameters that may be used when project-specific data are unavailable; deviations from these defaults should be justified and documented. Section 9.3 provides methodological guidance for converting activity data into life cycle inventory flows. Section 9.3.1 presents an example calculation for recurring maintenance activities, while Section 9.3.2 describes a general calculation method for estimating equipment energy use that can be applied to any life-cycle stage where construction or demolition equipment is used.

9.3.1 Stage B (Phases B2-B5)

All B2–B5 activities are time-dependent, typically recurring at scheduled or average intervals (e.g., re-coating steel every 15 years). For LCI analysis, converting these event-based scenarios into quantifiable flows is essential by translating discrete activities into material and energy inputs/outputs, averaged or aggregated over the bridge's Reference Service Life (RSL).

An example of a step-by-step breakdown is provided below:

1. Identify the Event-Based Scenario

Example: Re-coating steel railings every 15 years.

- Activity: Surface preparation (sand blasting) and Recoating
- Interval: Every 15 years
- Material: Epoxy paint
- Application Rate: e.g., 0.4 L/m²
- Surface Area: e.g., 500 m²
- Waste Rate: e.g., 5%
- RSL: e.g., 75 years

2. Calculate Number of Events Over RSL

   Number of Applications = RSL Interval / Interval = 75/15 = 5 applications

3. Multiply by Material and Energy Quantities

   Total Paint Required = = (0.4 L/m² × 500 m² × 5) + 5% =1,050 L

4. Convert Material Quantity to Mass or Embodied Emissions

   If the density of epoxy paint = 1.2 kg/L:

   1,050 L × 1.2 kg/L = 1,260 kg

   Multiply by emission factor (e.g., 2.5 kg CO_2e/kg):

1,260 kg×2.5 kg CO_2e/kg=3,150 kg CO_2e

For surface preparation by sand blasting:

Multiply by emission factor (e.g., 1.0 kg CO_2e/ m^2):

1.0 kg CO_2e/ m^2× 500 m² × 5= 2,500 kg CO_2e

Emission for surface preparation and painting= 3,150+2,500=5,650 kg CO_2e

5. Include impacts from supporting processes

- Equipment use e.g., airless sprayer, compressor
- Energy use: litres of diesel or kWh electricity
- Waste: leftover paint, VOC emissions, rinse water

Table 9-3: LCI example of flow entry (per functional unit over RSL)

Input/Output	Quantity	Unit	Notes
Epoxy paint	1,200	kg	5 re-coats over 75 years
Diesel (sprayer)	100	L	Based on 20 L per recoat cycle
Paint waste	60	kg	Assumed 5% overspray
VOC emissions	120	kg	Based on paint type and VOC content
CO_2 emissions	3,000	kg CO_2e	Embodied carbon of paint only

9.3.2 Equipment Energy Use Estimation (Applicable to All Life-Cycle Stages)

Equipment energy use may be estimated using equipment power ratings, load factors, and operating time. This method can be applied to construction, maintenance, and demolition activities, including Stage C (deconstruction and demolition).

- Quantify energy inputs based on equipment usage:

  Energy Use (MJ)=Power (kW) × Load Factor × Hours of Operation × 3.6

- Emissions from fuel combustion are calculated using region-specific emission factors:

  CO_2 Emissions (kg)=Diesel Use (L)×2.68kg CO_2/L

If multiple demolition stages are required (e.g., deck vs. substructure), analyze separately and sum flows.

9.4 Appendix D: Allocation

Allocation may be required in bridge LCAs when processes produce multiple outputs, such as industrial by-products (e.g., fly ash or slag) used in cement or when recycled materials are introduced into the bridge system. According to ISO 14044, allocation should be avoided whenever possible, as it can introduce uncertainty and complexity into LCA studies. However, when allocation is necessary, such as in the case of co-products, by-products, and recycled materials, it must be applied in a consistent, transparent, and justifiable manner. Two primary methods used for allocation are called cut-off method (also known as partitioning or subdivision) and the system expansion (also known as substitution) method. System expansion is acknowledged in ISO standards as an approach to avoid allocation altogether, rather than serving as an allocation method itself. Finally, the Mass/Energy/Economic allocation method is employed when cut-off or system expansion approaches are not feasible.

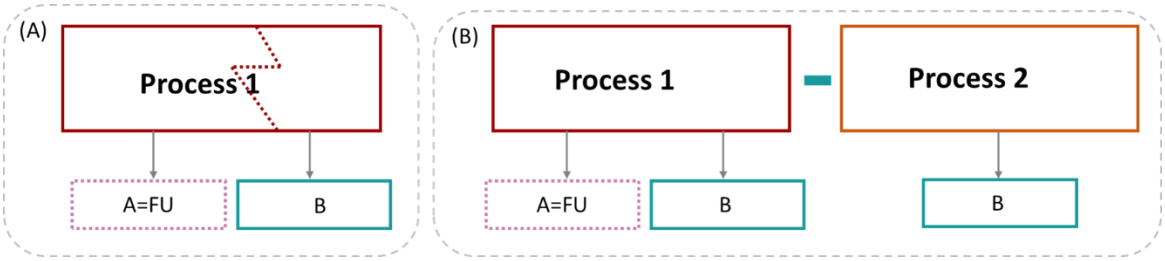


Figure 9-1: Conceptual illustration of partitioning and system expansion[85]: (A) Partitioning Inputs and outputs of process A are portioned over A and B based on a certain portioning coefficient. (FU=Functional unit); (B) System expansion Inputs and outputs of process 2 are subtracted from those of process 1

9.4.1.1 *Allocation methods*

(A) <u>Substitution/System Expansion Method</u>

The substitution method, also known as the avoided burden or system expansion method, gives credit to the original system for producing recycled materials. This is based on the idea that the first system benefits the environment by reducing the need for virgin materials (like concrete, steel, or asphalt) in subsequent systems. By supporting System 2, System 1 lowers its environmental impact. While this method is seen as more representative of circular economy outcomes, it adds complexity to modelling.

For processes with multiple outputs, the product system is expanded to include additional functions related to co-products. Although system expansion considers alternative production pathways for co-products, it can create chains of substitutions that loop endlessly, making LCAs (LCAs) less transparent and consistent. This approach is most effective when the material is valuable, readily available, widely used, and its production remains unaffected by demands

[85] Suh, S.; Weidema, B.; Schmidt, J.H.; Heijungs, R. Generalized Make and Use Framework for Allocation in Life Cycle Assessment. J. Ind. Ecol. 2010, 14, 335–353.

changes. It is particularly useful in markets that promote eco-friendly materials or aim to achieve long-term circularity goals in infrastructure design. However, it requires additional assumptions regarding future material use, quality retention, and market impacts.

(B) Cut-off/Partitioning Method

This allocation approach is usually applied to end -of-life or recycling modelling where the primary process gives a product and a co-product. The cut-off method assigns all end-of-life burdens to the original system (System 1) while excluding any benefits from recycling. In this approach, recycling processes are not accounted for within System 1 and are instead attributed as burdens or inputs to the next product system (System 2). Thus, the recycled materials are treated as waste for the current system and as input resources for the next. This approach is conservative and straightforward, particularly when tracking downstream use of recycled material is uncertain or outside the system boundary. It is frequently adopted in infrastructure LCAs where long material lifespans and variable reuse potential complicate end-of-life modelling.

LCA studies have shown that the choice between cut-off and substitution methods can have a significant influence on the outcomes of LCAs in the materials production stage (A1–A3)[86] and end-of-life stage (C1–C4)[87]. System expansion or substitution methods can introduce significant complexity and uncertainty due to the need to model and allocate impacts across multiple product systems, making them less practical and less transparent for standardized bridge LCA guidelines. This guideline suggests the cut-off method for consistency and transparency unless otherwise justified. This ensures emissions accounting is confined to the defined system boundary without speculating on future product systems.

(C) Mass/energy/economic Allocation Method

When allocation cannot be avoided, environmental burdens may be distributed based on physical relationships (e.g., mass or energy content). However, for construction products covered by Environmental Product Declarations, economic allocation based on revenue share is often required, consistent with EN 15804. Multi-output processes into single-output processes based on a relevant allocation factor (e.g., mass, energy content, economic value). This ensures that each output bears a fair share of the direct and indirect burdens, such as emissions, electricity, and raw material use. This method is suitable when multiple outputs are consistently co-produced (e.g., in cogeneration of electricity and heat), and no clear system boundary can isolate one output. However, this process can obscure cause-and-effect relationships and may be influenced by fluctuating market prices or physical parameters

9.4.1.2 *Allocation for Recycled and Reused Materials*

In bridge construction, materials can be recycled within the system (e.g., reusing crushed concrete from an old bridge in a new bridge foundation) or imported from external systems (e.g.,

[86] Cherubini, F., Strømman, A. H., & Ulgiati, S. (2011). Influence of allocation methods on the environmental performance of biorefinery products—A case study. Resources, Conservation and Recycling, 55(11), 1070-1077. https://doi.org/10.1016/j.resconrec.2011.06.001

[87] Nicholson, A. L., Olivetti, E. A., Gregory, J. R., Field, F. R., & Kirchain, R. E. (2009, May). End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. In 2009 IEEE international symposium on sustainable systems and technology (pp. 1-6). IEEE. https://doi.org/10.1109/ISSST.2009.5156769

using industrial by-products like fly ash). The following cut-off criteria should guide allocation decisions:

- *F*or materials recycled within the same system:
    - Exclude the original manufacturing and construction processes.
    - Include transportation and processing if reused on-site.
    - Include demolition but exclude further processing if the material is removed from the system.
- For materials imported from external systems:
    - Include transportation and processing required for use.
    - Account for any additional environmental impacts from incorporating these materials into the new system.
- For materials sent to landfill:
    - Include demolition, transportation, and landfill processing.

Materials should not be classified as waste if they retain economic value. Instead, they should be treated as co-products, which require allocation based on mass, energy, or economic value. While substitution can reward recyclability, it brings considerable modelling complexity and uncertainty. It requires assumptions about future recycled material use, which may not be valid, and poses a risk of double-counting if both systems claim credits. Open-loop recycling increases the need for allocation between systems, and the endless regression problem can arise from nested coproduct relationships. Due to these limitations, this guideline adopts a 100% cut-off (partitioning) approach for bridge LCA, promoting conservative, consistent, and traceable results aligned with other Canadian LCA practices.

9.4.1.3 *Allocation Procedures for Co-Products and Wastes*

When allocation cannot be avoided, the following procedures should be used:

- *Physical Allocation*: Partition environmental impacts based on measurable physical properties such as mass, energy content, or volume.
- *Economic Allocation*: Distribute impacts based on the relative economic value of each co-product. This should only be used when physical allocation is not feasible.

If multiple allocation methods are applicable, performing a sensitivity analysis can help in understanding the range of possible outcomes and the robustness of the results. ISO guidelines recommend that allocation procedures should be uniform across similar products to maintain comparability.

9.5 Appendix E: LCA Tools and Software

The major software packages used to perform LCA are GaBi, SimaPro, OpenLCA, OneClick LCA and Tally. Some domain specific programs such as Athena Pavement LCA are also available. However, there is lack of such tailored tool for bridge infrastructure. Different applications of the LCA methodology have been described in the literature with the purpose to evaluate the environmental impacts caused using traditional and alternative materials in infrastructure construction. There are various tools that assess the sustainability of infrastructure. Examples of these tools are Athena, PaLATE and BE2ST. These tools incorporate economic and environmental variables in the analysis, showing the benefits of the use of alternative materials and facilitating the decision-making of the builders and the public sector when deciding on the material to use.

Tables 9-4 presents a list of common LCA tools and software with potential use and application for bridge LCA modelling. Some of these tools were specifically tailor-designed for construction and infrastructure applications and some are general LCA tools which can also be used for infrastructure design and construction purposes.

Table 9-4: Tools/Software

Tool/Software	Description and Application
SimaPro	Supports EPDs, GHG protocol and ILCD system handbook
Gabi	Includes advanced features such as scenario analysis, system expansion and process-based LCA.
OpenLCA	Open-source LCA software. Allows LCA modelling using several databases and multiple LCIA methods.
eToolLCD	Web-based tool for life cycle analysis of industrial projects, infrastructure and buildings. Allows cradle to grave analysis and modelling of carbon emissions, waste, energy use and water use.
Other Commercial LCA Tools and Software	OneClick LCA
LCA Bridge Toolkit	Bridge-specific tool developed by FHWA in the US. Used to evaluate the environmental performance of different bridge materials, design and construction alternatives.
Other open-source tools	tallyLCA EC3 Athena Pavement LCA

Bridge LCA model

A bridge LCA Model was developed by Du and Karoumi (2014)[88] for railway bridge structures in Sweden). With multi-levels of detail, this model serves as a generalized framework to assess the environmental performance of the bridge system from a whole life cycle perspective, either for the entire bridge or given structural components. The model considers the bridge structural elements and connects them to specific material types. The life cycle inventory data with embedded manufacturing process are further assigned to the selected material. This model is treated as the input to the LCA.

CO2NSTRUCT

It is a LCA approach for road transport infrastructure in evaluating GHG emissions. The tool's database consists of 80 materials, 105 construction machines, 42 energy sources, 8 electricity mixes, 80 categories of environmental systems, 10 types of waste and 21 transport vehicles used in road projects in Spain. National data and information were favored, where available, but European references were relied upon where these were lacking. This criterion was adopted to increase the accuracy of tool results in the case studies. Nevertheless, the tool can be fed with local data for every new analyzed project, to ensure precise results. The actual CO_2NSTRUCT tool[89] its project database is intended for private use in Spain and therefore can't be made available publicly. The scheme of the principal elements of the application, as well as its respective breakdown for contamination phases, is shown in **Figure 9-2**. The main activities that lead to GHG emissions are the operation of off-road machinery, the performance of facilities, transportation (materials, machinery, wastes), processes of extraction and production of construction materials, waste processing, and management of environmental systems (disruption and restoration of soils and vegetation). Energy consumption has been acknowledged as the main cause of emissions underlying those activities. In each case, emission factors are defined by reference to a unit quantity, operating time or energy.

[88] Du, G., & Karoumi, R. (2014). Life Cycle Assessment framework for railway bridges: literature survey and critical issues. Structure and Infrastructure Engineering, 10(3), 277-294. https://doi.org/10.1080/15732479.2012.749289

[89] Fernández-Sánchez G, Berzosa Á, Barandica JM, Cornejo E, Serrano JM. (2015). Opportunities for GHG emissions reduction in road projects: a comparative evaluation of emissions scenarios using CO2NSTRUCT. Journal of Cleaner Production.104:156-67. https://doi.org/10.1016/j.jclepro.2015.05.032

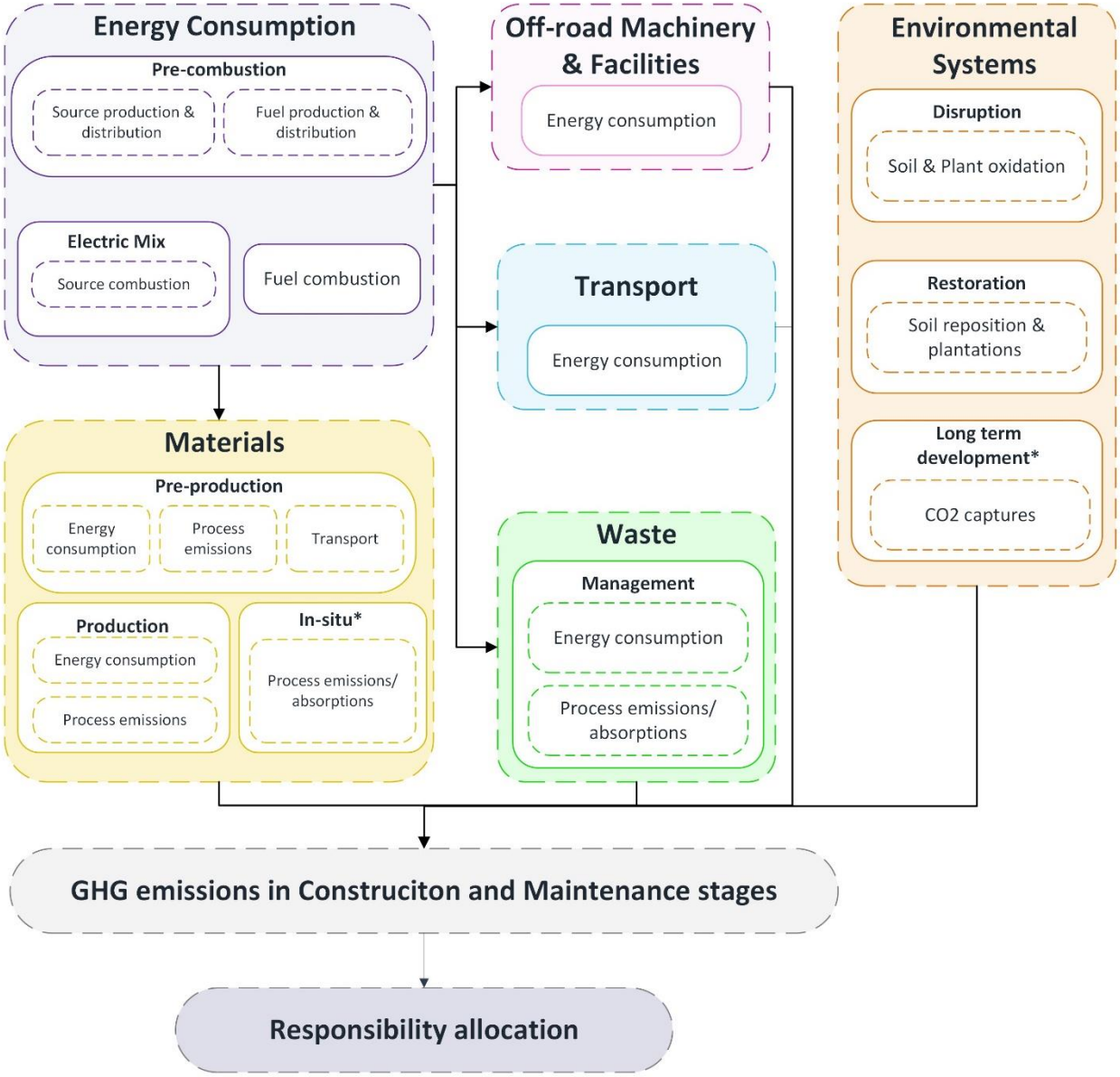


Figure 9-2: Scope of the analysis of CO_2NSTRUCT (*: processes that are unique to the maintenance stage; shaded areas indicate the level at which emissions are counted)[90]

[90] Barandica, J. M., Fernández-Sánchez, G., Berzosa, Á., Delgado, J. A., & Acosta, F. J. (2013). Applying life cycle thinking to reduce greenhouse gas emissions from road projects. Journal of cleaner production, 57, 79-91. https://doi.org/10.1016/j.jclepro.2013.05.036