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INTERNATIONAL AEROSPACE ENVIRONMENTAL GROUP®

Aerospace Life Cycle Assessment (LCA)

Framework for improved connectivity

April 2025

Version ***01***

This document is released for purpose of providing a guidance for aerospace companies to enhance the connectivity of their LCAs

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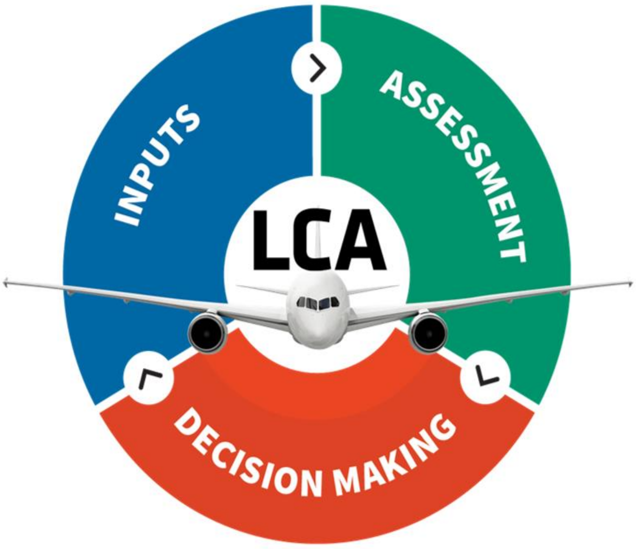

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Version History

Date	v#	Modified By	Section, Page(s) and Text Revised
22 April 2025	1	Garcia Garriga, A.	First released version

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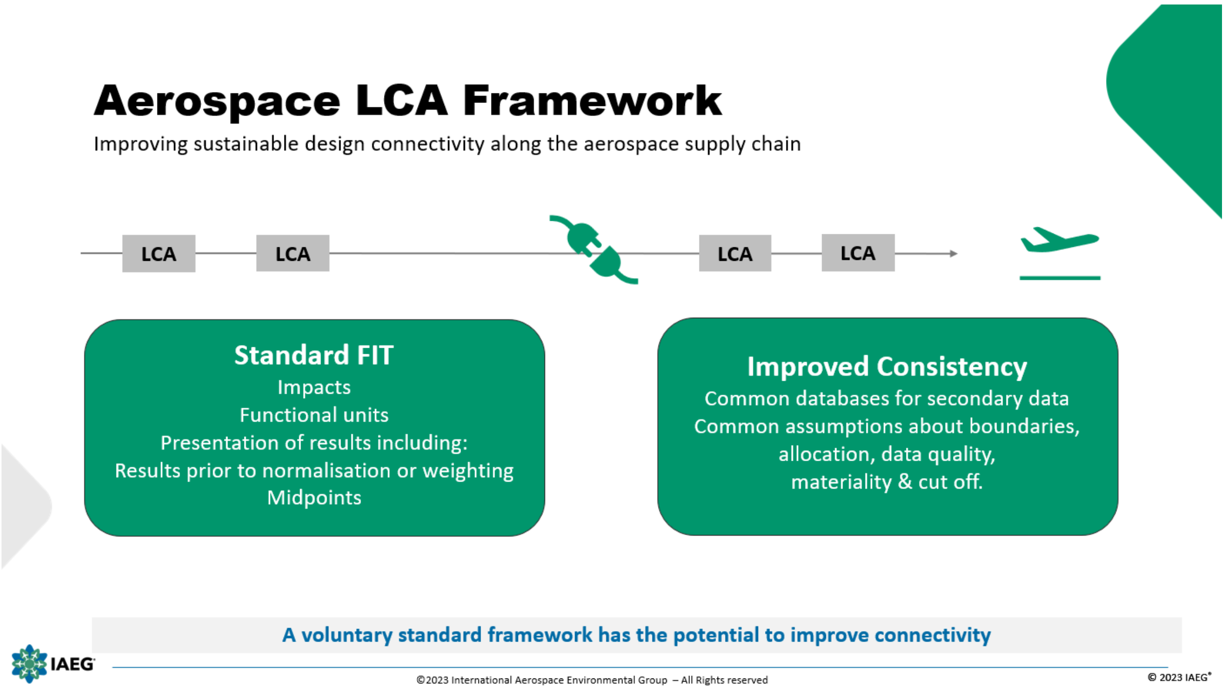
EXECUTIVE SUMMARY

IAEG seeks to develop voluntary leading-edge solutions across the value chain to promote a responsible and sustainable aerospace industry. The purpose of this document is to offer a standard framework for Lifecycle Assessments (LCA) to companies that design and manufacture products for aerospace. Version 1 of this standard framework is intended to improve the connectivity of LCA along the aerospace supply chain, both in terms of 'fit' and 'consistency'.

Improved fit means that the outputs of an aerospace LCA match the required inputs of the LCA of the next level in the supply chain. Improved consistency means reducing the unwanted variation in the LCA process. This will reduce wasted effort and improve the value of LCA outputs. Benefits include building stakeholder confidence in aerospace LCA and preparing for emerging regulations.

It is also important that the aerospace sector takes the opportunity to build sustainability into its design processes to inform design and manufacturing choices and accelerate progress.

Much of the guidance in this framework is offered as a 'baseline' that companies may either choose to use or add to as they wish. IAEG would very much welcome further engagement and feedback to help add even more value to Version 2 of this standard framework.



Aerospace LCA Framework

Improving sustainable design connectivity along the aerospace supply chain

Standard FIT

Impacts

Functional units

Presentation of results including:

Results prior to normalisation or weighting

Midpoints

Improved Consistency

Common databases for secondary data

Common assumptions about boundaries, allocation, data quality, materiality & cut off.

A voluntary standard framework has the potential to improve connectivity

Jump Ahead

Key parts of the Aerospace LCA Framework in this document are highlighted in boxes like this one

Acronyms

BoM – Bill of Materials

CBAM- Carbon Border Adjustment Mechanism

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation

CSRD- Corporate Sustainability Reporting directive

EF – Environmental Footprint

EOL – End of Life

EPD – Environmental Product Declarations

FU – Functional Unit

GHG – Greenhouse Gas

IAEG – International Aerospace Environmental Group

IATA – International Air Transport Association

ICAO – International Civil Aviation Organization

ISO – International Organization for Standardization

IP – Intellectual Property

KPI – key performance indicators

LCA – Lifecycle assessment

LCIA –Lifecycle Impact Assessment

OEF – Organization Environmental Footprint

PCR – Product Category Rule

PEF – Product Environmental Footprint

SAF – Sustainable Aviation Fuel

1 INTRODUCTION

This section serves to introduce the basic principles of Lifecycle Assessment (LCA) and the purpose of this document to establish a voluntary common framework for aerospace companies to carry out LCAs for their products.

1.1 What is Lifecycle Assessment?

Lifecycle Assessment is a method for identifying the potential environmental impacts of a product, process or activity over its entire life cycle from the extraction of the raw materials to the end-of-life of the product. A typical product lifecycle is presented in Figure 1. It is one of several widely practiced disciplines that shows environmental impact using quantitative data. LCA serves as a critical tool for informed decision-making, fostering innovation and guiding the industry toward more sustainable practices.

Figure 1. Lifecycle of an aerospace product

If you are unfamiliar with Lifecycle Assessment, please refer to Appendix A for an overview of the topic

1.2 When did LCAs emerge?

Lifecycle assessment emerged as part of a growing interest in quantifying the environmental impact of products and services in the context of increasing concern over human impacts in the environment such as climate change and depleting natural resources. The gathering of environmental data and evidence, and setting targets and roadmaps based on that data has become commonplace at national, industrial and company levels in order to support funding & investment, establish eligibility criteria for contracts, and define strategies.

Due to its growing importance, and the need to avoid misuse, Lifecycle assessment principles and its base framework were codified in an international standard in ISO:14040[1] in 2006, which was later amended in. Many industries have since adapted the principles contained in the ISO standard to their specific needs.

1.3 Who is involved in LCAs in aerospace?

In Aerospace, our products, supply chains and technologies are global and very complex. Protecting intellectual property, complying with global trade restrictions and maintaining a competitive advantage create barriers to data sharing across the aerospace value chain. These barriers present a challenge when collaboration is required to construct a quantitative lifecycle analysis across the value chain that preserves data quality while adhering to the data sharing restrictions of the industry.

Many Aerospace companies participate in the creation and interpretation of lifecycle assessments of aerospace vehicles and final products. Achieving added value from lifecycle assessments require consistent data harvesting and analytical methods utilization by all involved and agreement on each partners role and data boundaries. This document seeks to implement the principles of ISO:14040 and other recognized standards in LCA to the aerospace industry to reduce the variability in data harvesting and calculation method across aerospace companies.

1.4 Why carry out LCAs?

There are a variety of reasons for carrying out lifecycle assessments. These include but are not limited to:

- Benchmark current product environmental performance and raise awareness
- Address and reduce environmental impacts across the value chain
- Avoid burden shifting and unintended consequences
- Conserve resources and reduce costs
- Improve the quality of products over time
- Strengthen customer loyalty by demonstrating a proactive approach to environmental challenges and abide by customer requirements
- Minimize supply chain risk by pacing ahead of environmental regulations

Assessments can be generated for private use in teams, companies, memberships or shared externally to customers or the general public. It is therefore important that there is a shared voluntary standard on data and methodology that allows for some flexibility depending on the end objective and final reach of the assessment while maintaining data quality and limited variability. Without this, collaboration on defining the environmental impact of aerospace products is difficult and quantifying improvement on their overall environmental impact becomes very challenging.

1.5 Where to define a voluntary framework to carry out aerospace LCAs?

Since 2011 IAEG has been an effective voluntary platform for organizations across Aerospace and Defense to collaborate and share voluntary solutions to the environmental challenges in the industry. The IAEG 2030 vision for a sustainable aerospace and defense industry includes developing harmonized solutions and encouraging adoption across the Aerospace Value Chain. IAEG releases voluntary guidance and offers opportunities for collaboration across a number of topics, in 2023 the IAEG included a working group on lifecycle assessment (WG12) in order to tackle some of the challenges outlined herein.

This framework document collates the distilled best practices and recommended methods and approaches from the shared experiences of WG12 volunteers on life cycle assessment work and research. The end goal is to ensure that meaningful and high value assessments can be achieved effectively and efficiently across value chains by agreeing on a set of principles and methods upfront across the industry.

Lifecycle Assessment is part of a wider effort to reduce the environmental impact of aerospace products and ensuring we have the tools and methods to quantify and mitigate impacts. The guidelines in this document are proposed to streamline efforts, reduce variation, and simplify practices across a variety of environmental sustainability reporting and when quantifying commitments.

1.6 How does this document help aerospace companies with their LCAs?

IAEG WG12 has created this guidance document to help align Aerospace and Defense parties into shared practices that will lead to minimized unnecessary variations in LCA outputs and a reduction in duplicated efforts

IAEG WG12 comprises LCA practitioners who compile and create assessment, recipients of life cycle analysis who use assessments as well as volunteers from diverse Aerospace roles. This collaboratively developed document therefore distills shared visions, best practices and knowledge to support LCA guidance leading to maximum shared value throughout our supply chains and wider aerospace ecosystem.

The principles and guidelines in this document have been provided to encourage best cohesion in practitioners, participants, and recipients of LCAs independent of the level of LCA maturity of the individual or organization. However, due to the complex nature of LCA, some prior knowledge of the basic nomenclature and principles of LCA are needed to understand the details of some of the recommended approaches in the later sections of this document.

If the reader is a novice to LCA or wishes a refresher on the basic principles, Appendix A in this document offers a short primer to understand the basics of LCA.

In the main body of the document, from Section 2 on, background information, systems logic, analytical mechanisms, and practical guidelines are provided so that individuals with LCA responsibilities can use to maximize industrial alignment.

This content was defined in the following process: IAEG WG12 used academic sources and member experience to identify 'Framework Questions'. These were the choices frequently encountered by aerospace companies seeking to build or develop their approach to LCA. For example, which environmental impacts to include or how to present results. These Framework Questions were researched, and the generic alternative answers and approaches identified. The benefits and drawbacks of these generic answers were considered within an aerospace context. An aerospace baseline answer was proposed and tested by peer review and discussion. These 'Framework Answers' have been included in this document. In general, the 'framework answers' and recommended methods are in grey boxes and narrative text are presented in standard white background.

Transition to a robust sharable industrial practice may take time to fully develop. This is intended to document best practices as they stand today and are understood by IAEG WG12 members. As more companies adopt the principles and test their effectiveness, this will steer the further development of LCA practices in Aerospace. IAEG WG12 welcomes further engagement and feedback with the guidelines contained in this document to help add even more value to subsequent versions of this standard framework

1.7 Structure of the document

This document is structured as follows:

- Section 2 covers some of the potential use cases for Lifecycle Assessment
  and how they define some of the key requirements for the LCA process itself
- Section 3 will then cover the basic methodology of an LCA and some data principles to follow when carrying out an LCA study.

- Section 4 then includes some consideration for LCA tool selection and LCA dataset providers.
- Section 5 details the recommended approaches for the output results of an LCA.
- Section 6 covers the review process for the LCA data.

2 USE-CASES

This section examines key use cases where LCA is applied to support various stages of sustainability integration. A preliminary assessment of diverse applications has been conducted within IAEG WG12 members to enhance visibility into how aerospace companies are utilizing LCA and the specific objectives they aim to achieve.

Aerospace products typically have extended supply chains from raw materials to end users. As such, all aerospace use cases of LCA are likely to require supply chain collaboration and benefit from improved supply chain data. In the case that suppliers are responsible for design for aerospace and use LCA, it is even more important to reduce unwanted variation in the LCA process itself. This can aid in reducing wasted effort at the aircraft programme level and beyond. Process consistency also helps improve stakeholder confidence is aerospace LCAs and the decisions they support.

Lifecycle Assessments (LCAs) are commonly used both internally to the aerospace companies and to produce external declarations. This section will first cover the internal use cases (Subsections 2.1-2.4) and then the external release use case, commonly through **Environmental Product Declarations (EPDs)**—documents that provide verified data on a product's environmental footprint. EPDs are intended for diverse audiences, including customers, and stakeholders, and the general public and are developed following the international standard **ISO 14025**[2]. This standard emphasizes the need for **Product Category Rules (PCRs)** to produce EPDs for external release.

2.1 Assessment and Understanding

Purpose: This foundational use case aims to quantify and understand the environmental impacts associated with materials, resources, products, and processes throughout their lifecycle.

Approach:

- **Data Collection**: Gather high-quality, relevant data across all stages of the lifecycle, including raw material extraction, manufacturing, transportation, use, and end-of-life.
- **Hotspot Analysis**: Identify critical stages, materials, or processes contributing most significantly to environmental impacts (e.g., carbon emissions, energy consumption, resource depletion).
- **Tool and Framework Utilization**: Leverage established LCA software and standards (e.g., ISO 14040/14044) to ensure robustness and comparability of results.
- **Iterative Refinement**: Refine data and assumptions based on preliminary findings to improve accuracy and representativeness.

Outcome: The assessment provides a comprehensive baseline understanding of environmental performance, serving as the foundation for decision-making, benchmarking, and continuous improvement.

2.2 Requirements and Objectives Definition

Purpose: This use case translates insights from the assessment phase into actionable environmental objectives and performance requirements for aerospace projects.

Approach:

- **Setting Environmental Goals**: Define specific, measurable, achievable, relevant, and time-bound (SMART) objectives (e.g., reducing lifecycle carbon emissions by 20% over five years).
- **Compliance and Standards Alignment**: Ensure objectives align with relevant regulations, standards (e.g., ICAO Carbon Offsetting and Reduction Scheme for International Aviation - CORSIA), and industry benchmarks.
- **Performance Metrics**: Establish clear key performance indicators (KPIs) to track progress toward objectives.
- **Integration with Design Requirements**: Embed environmental goals into project specifications, ensuring they are considered alongside technical and economic constraints.

Outcome: A clear roadmap that integrates sustainability into the design, development, and operational phases of aerospace projects, ensuring alignment with strategic and regulatory priorities.

2.3 Comparative and Scenario Assessment

Purpose: This use case evaluates and compares multiple design, material, and process scenarios to identify the most environmentally friendly options while meeting performance requirements.

Approach:

- **Scenario Development**: Define alternative designs, materials, or processes for comparison (e.g., aluminum vs. composite materials, conventional vs. additive manufacturing).
- **LCA-Based Comparison**: Use LCA tools to assess the environmental impacts of each scenario across multiple dimensions, such as greenhouse gas emissions, energy use, and resource depletion.
- **Trade-Off Analysis**: Evaluate trade-offs among environmental benefits and other factors, such as cost, weight, and performance.
- **Sensitivity and Uncertainty Analysis**: Test how variations in input assumptions affect outcomes to ensure robust decision-making.

Outcome: A prioritized set of recommendations that enable the selection of designs, materials, or processes with the least environmental impact while fulfilling project objectives.

2.4 Reporting and Communication

Purpose: This use case focuses on effectively reporting LCA findings, ensuring regulatory compliance, and communicating results to internal and external stakeholders.

Approach:

- **Clear Documentation**: Prepare comprehensive yet accessible reports detailing LCA methodology, assumptions, and results in compliance with relevant standards (e.g., ISO 14025 for EPDs).
- **Stakeholder-Specific Messaging**: Tailor communication to intended audiences:

  - **Internal Teams**: Highlight actionable insights to inform design, procurement, and operations.
  - **Customers and Partners**: Demonstrate sustainability efforts and product environmental performance.
  - **Regulators and Certifying Bodies**: Ensure compliance and facilitate certifications.
- **Visualization Tools**: Use charts, infographics, and dashboards to make complex LCA data more understandable and engaging.
- **Transparency and Verification**: Where applicable, seek third-party verification to enhance credibility and stakeholder trust.

Outcome: Clear, credible, and actionable communication of LCA results, supporting informed decision-making, compliance, and stakeholder engagement throughout the aerospace supply chain.

2.5 Environmental Product Declarations & Product Category Rules

As introduced earlier, Environmental Product Declarations (EPDs) are a particular use case of environmental impact communication to external stakeholders governed by specific principles following the international standard ISO 14025 requiring Product Category Rules (PCRs) to produce EPDs for external release. This framework document does not replace PCRs for specific aerospace products and is intended to complement existing standards including ISO 14025 with specific aerospace guidance.

PCRs are guidelines that define the requirements for conducting LCAs and developing EPDs for specific product categories. It ensures consistency, transparency, and comparability in assessing and reporting environmental impacts.

In the aerospace sector, the supply chain encompasses a wide range of components, materials, and processes, each with distinct functional units reflecting their role in the final product. While PCRs are designed for specific product categories (e.g., an aircraft or subsystem), a single PCR cannot address the diversity of functional units across the entire supply chain.

The IAEG LCA Framework addresses this complexity by offering guidance to enhance consistency and compatibility across the aerospace supply chain. Rather than replacing existing PCRs, the framework aligns methodologies and data practices, ensuring LCAs conducted at different supply chain stages are robust, interoperable, and aligned with industry standards. When drafting a PCR for an aerospace product in the future, the framework document could serve as the basis for a common methodology and principles, removing unwanted inconsistencies across different aerospace PCRs.

By standardizing key elements such as **impact categories and data quality**, the framework enables practitioners to produce LCA results that integrate seamlessly. In summary, the IAEG LCA Framework equips supply chain actors with the tools to perform LCAs more effectively, fostering collaboration and enhancing the quality of environmental reporting across the aerospace industry while preserving protection of IP and compliance to export control rules in the data exchange by prioritizing the sharing of the LCA results in a hierarchical LCA rather than the product details. More detail on how the different use cases can be applied throughout the product lifecycle are present in Appendix B.

3 METHODOLOGY

The use of standardized methodology ensures consistency and reliability in LCA studies. ISO 14040 and ISO 14044 provide a systematic approach to evaluating the environmental impacts of products and processes throughout their entire lifecycle. However, these standards are general-purpose and not specific to aerospace products. This sub-section outlines the IAEG recommendations for determining boundaries and scope for an aerospace LCA, data collection, the various lifecycle stages, as well as impact categories and calculations to ensure consistency across the industry.

3.1 LCA Goal Setting and Elements

For any LCA, the goal of the study must be clearly stated. ISO requires that the goal statement include unambiguous statements about four key aspects: (1) the reasons for carrying out the study, (2) the intended application/use, (3) the intended audience, and (4) whether the results will be used in comparative assertions released publicly or not.

Other elements that should be stated upfront include the relevant parties involved in carrying out the LCA and any potential limitations the study includes.

This section is divided into five elements which must be identified and reported on in any LCA:

1. Study goals (reason for the LCA study)
2. Intended application of the study
3. Target audience (links to deliverables and results communication)
4. Commissioner (customer) of the study and other influential actors
5. Limitations of method, assumptions, data etc.

3.1.1 Study Goals

The purpose of the study results should be clearly defined to avoid the results being interpreted and applied out of context.

The most common LCA goals include benchmarking the environmental impact of an individual product (good or service) and the relative contributions of different materials and processes, to support the development of environmentally optimal products by modelling various scenarios and establishing design requirements on environmental sustainability or to release claims about the environmental impact of your product externally whether comparing it to a previous product or a competitor's product. These are covered in some more detail in the Use Case section (Section 2) earlier in the document.

As part of the study goal, it is important to clarify the target product or service the LCA will focus on. The target representative product or system can be defined as either:

- **A simulated product:** When sufficient market and technical information is available. The simulated product must be calculated based on weighted characteristics like weighted average sales of all existing technologies/materials covered by the scope of the LCA, or by weighted average mass (ton of material) or weighted average product units (pieces).

- **A real product:** When the market or application is made up of different technologies, but incomplete market and/or technical information are available. A real product sold can be chosen as the representative product.

These study goals and the target product being stated upfront help define the level of data quality and scrutiny the study has undergone and adds necessary context to the LCA to help with the interpretation of results.

3.1.2 Intended Application

The intended application of the study expands on the overall study goal and pinpoints the specific use the LCA is intended for beyond the stated goal. As an example, whereas the goal of the study might be to release environmental performance information of your product externally, the intended application is to do so in an eco-label with a specific set of requirements.

The intended application must be identified and clearly stated in the final report. This is critical for framing the context and understanding the value add the study will bring. Some examples of applications common to aerospace include:

- Comparative study to compare the environmental impacts of different products systems with the same functions
- Identifying hotpots where the most significant environmental impact occurs over the lifecycle of a product system.
- Evaluating improvement of design and process choices during decision making
- Reporting of environmental impacts, responding to policy and legislative requirements
- Producing an eco-label
- Producing an EPD based on a PCR
- Support policy development which considers environmental impacts

3.1.3 Target Audience

The target audience should be identified and reported on, this will include the study commissioner and all key stakeholders. Identifying the intended audience is key to ensuring alignment of your project with the needs of your audience. LCA involves transforming great amounts of raw data into useful information – and what is considered useful depends on who the audience and the intended application of the project are.

By having the audience in mind at the start of the LCA project, the style and presentation of the LCA report itself can be adapted to aid understanding and capture interest. This can also minimize the risk that the readers will misinterpret the results. Once the target audience has been identified, and the application and study purpose are clearly defined, the deliverables should be evident. There may be some deviation in the deliverables based on the specific requests of the commissioner.

3.1.4 Commissioner

The commissioner (name and contact) must be identified and reported. This provides the audience of the LCA a point of contact for study and the organization or person(s) that created it, allowing visibility of any bias that might be included from that position. For example, an LCA carried out by an academic institution will have a different focus than one created by the product owner to promote its benefits.

3.1.5 Limitations

Upfront limitations of the study should be summarized during the goal definition. Limitations shall cover as needed: methods used, impact categories studied, data quality and breadth and software and process implemented.

While limitations are more extensively discussed in the interpretation of results portion of an LCA study, stating the major limitations upfront can help manage the expectations of the audience for the study and offers more clarity on the breadth and depth of the study presented.

3.2 LCA Scope Definition

The scope definition of the lifecycle assessment is necessary to identify what product systems are to be assessed and how assessment will occur. The scope is where the system under study is characterized, assumptions are detailed and the methods used are defined.

The study scope is not a single statement like the goal, but a collection of qualitative and quantitative information denoting what is included in the study, and key parameters that describe how it is done.

There are six elements to the scope definition which are to be considered and documented for completeness of any study.

- Functions (Section 3.2.1)
- Functional unit (Section 3.2.2)
- Reference flows (Section 3.2.3)
- System boundaries (Section 3.2.4)
- Exclusion criteria (Section 3.2.5)
- Modelling approaches (Section 3.2.6)

The study scope relies on the goal setting elements explained in the previous section (3.1), as the study requirements vary depending on the stated goal. For example, comparative LCAs or LCAs to be released externally set more stringent requirements on boundaries, exclusions, modelling approaches, etc.

3.2.1 Functions

A product system (as defined in ISO 14040:2006) is a collection of processes that provide a certain function. Functions in LCA describe the primary purpose or role of the product or system being assessed. They are essential for understanding what the product is designed to achieve or the service it provides. Some aerospace examples of functions are included in the table below and illustrated in Figure 2.

Table 1. Example Functions for aerospace products

System	**Function**	**Comment**
Jet engine	To produce thrust	Generates a force through combustion of gases (transforms chemical energy to heat energy)
Aircraft wings	To generate lift	Lift is the upward force that allows an aircraft to stay airborne
Landing gear	To absorb and dissipate kinetic energy when landing	Protects the aircraft from damage and ensures a smooth touchdown
Aircraft	To transport people and/or cargo	Combines various subsystems including the jet engine, aircraft wings, and landing gear described above, to achieve a controlled flight

Aircraft Wing: to generate lift (Ref)

Landing Gear: to mitigate the impact of landing (Re

Figure 2. Examples of functions

3.2.2 Functional Unit (FU)

The functional unit (FU) is a quantified measure of the function(s) provided by the system of interest. It serves as a reference point for all inputs and outputs in the LCA. The functional unit describes and quantifies those properties of the product, which must be present for the studied substitution to take place. These properties like its functionality, appearance, stability, durability, ease of maintenance, etc., are determined by vehicle requirements defined through customer or market input.

The functional unit is crucial because it allows for the comparison of different products or systems on a common basis. It ensures that the assessment is consistent and meaningful.

Table 2. Example functions for aerospace products

System	Function	Functional unit
Jet engine	To produce thrust	Generate 200 kN of thrust for sustained flight
Aircraft wings	To generate lift	Generate sufficient lift to support 100,000 kg
Landing gear	To absorb and dissipate kinetic energy when landing	Absorb 1.5 MJ of energy during landing
Aircraft	To transport people and/or cargo	Transport a passenger/a kg of payload 10,000 nautical miles

For instance, in the case of a single aisle aircraft, the functional unit could be defined as "transporting 135 passengers across a distance of 1,000 nautical miles." This means that all environmental impacts will be calculated based on the resources and emissions associated with transporting the 135 passengers across the defined distance. Other examples include:

- **Widebody Aircraft:** "Transport 525 passengers across a distance of 7,200 nautical miles." or when comparing means of transport: “Transport one passenger between city A and city B”
- **Aircraft Paint:** “Provide protection of 1 m^2 area substrate for 30 years with a minimum 95% opacity.”


Aircraft: Transport 525 passengers (Ref)

Aircraft Paint: Provide protection of 1 m^2 substrate for 30 years (Ref)

Figure 3. Examples of functional units

Recommended functional units for certain use cases and vehicle types are detailed in the Appendix C.

The FU of an aerospace LCA should describe qualitatively and quantitatively the function(s) and duration of the product/component/system using the following four questions:

- The function(s) or service(s) provided, i.e., “**what?**”
- The extent of the function or service, i.e., “**how much?**”
- The expected level of quality, i.e., “**how well?**”
- The duration or lifetime of the product, i.e., “**how long?**”

It is recommended that an aerospace LCA explain and document any functional omissions related to the product, component or system when defining the functional unit.

The FU of intermediate products or systems is more difficult to define because they can often fulfill multiple functions and the whole lifecycle of the product may not be known Thus, it is recommended that a declared functional unit be applied, e.g., mass (kilogram) or volume (cubic meter).

For example, the functional unit of a whole vehicle might be “to transport 135 passengers 1500 nm” but the aircraft paint provider does not necessarily have visibility on that end function. For an intermediate product a more appropriate FU might be: “to paint 1m^2 with the desired coverage”. However, the vehicle integrator might purchase the pain based on volume or mass and not coverage. Therefore, a useful functional unit for LCA data transfer would be to declare the LCA impacts based on a functional unit of “1kg of paint”. It would then be up to the paint provider to also report it based on area coverage. An illustration of this is included in *Figure 4*.

To enable transfer of LCA data across aerospace, IAEG recommends LCA data be provided with a mass or part count based functional unit. A data provider may additionally elect to declare their own selected functional unit and report it as a fraction of the product’s mass or “per product”. The lifecycle inventory (LCI) data per selected function unit can then be derived while maintaining the consistent reporting methods of mass and part count functional units. The intent of a selected functional unit is to allow representation of a product’s superior utility and a faithful representation of the products impact in their normal function that is otherwise not represented by mass. See *Figure 4* for an example.

$$\overbrace{\frac{\mathit{Environmental\ Impacts}}{\mathit{Mass}}}^{\text{Recommended, for value chain communication}} \times \overbrace{\frac{\mathit{Mass}}{\mathit{Relevant\ Functional\ Unit}}}^{\text{Optional, declared, selected by the provider}} = \overbrace{\frac{\mathit{Environmental\ Impacts}}{\mathit{Relevant\ Functional\ Unit}}}^{\text{Optional, derived, focused on provider claims}}$$

$$\overbrace{\frac{CO_2 emissions}{kg\ of\ paint}}^{\text{Paint supplier provides as an LCA result downstream}} \times \overbrace{\frac{kg\ of\ paint}{m^2\ \ covered\ with\ minimum\ opacity}}^{\text{Paint supplier declares alongside LCA results}} = \overbrace{\frac{CO_2 emissions}{m^2\ \ covered\ with\ minimum\ opacity}}^{\text{Paint supplier uses as a metric of environmental performance}}$$

Figure 4. Required and Selected Functional Units

An aerospace LCA should describe how each aspect of the functional unit can affect the environmental footprint of the product, component, or system. It is recommended that the LCA capture how the appropriate reference flows were calculated, which are described in the next section. Applicable standards should be used and cited in the LCA when defining the FU.

3.2.3 Reference Flows

Reference flows are the amounts of products, materials, or energy required to fulfill the functional unit. They are used to quantify the inputs and outputs in the LCA. Reference flows translate the functional unit into specific quantities of materials and energy and are essential for inventory analysis, where all inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) are quantified. For example, to transport 135 passengers you might require one aircraft with 135 passenger capacity, or several aircraft with lower capacity until you can fulfill the functional unit. Each of those aircraft will require a certain amount of water, fuel and other fluids. These quantities constitute the input and output flows and shall be scaled accordingly to the reference flow.

For the functional unit of " to transport 135 passengers," the reference flows might be an aircraft with a capacity of 135 passengers that for the flight portion might include as inputs (numbers are for illustration purposes only):

- Water - 200 liters
- Fuel loaded - 5,300 liters of fuel (Jet A)
- Hydraulic fluid - 30 kilograms of hydraulic fluid

And as outputs:

- Waste water - 125 liters
- Fuel consumed- 5,300 liters of fuel (Jet A)
- CO2 emissions from fuel burned – 13,810 kgs CO2

These reference flows are illustrated in the figure below.

Figure 5. Example of the reference flow and its inputs and outputs for a functional unit of "to transport 135 passengers 1500 nmi"

The function, functional unit and reference flows are interconnected as the function and functional unit define the scale and applicability of the reference flows for a particular product or process.

Table 3. Example of reference flow and functional unit relationship

System:	**Aircraft**
Function:	To transport people
Functional unit (FU):	Transport a single passenger 2,000 nautical miles
Reference flows:	• Aircraft 1 (narrow body) — capacity 135 passengers • Aircraft 2 (widebody) — capacity 525 passengers
Performance:	Aircraft 1 — 5,000 litres of fuel consumption per 2,000 nautical miles Aircraft 2 — 10,000 litres of fuel consumption per 2,000 nautical miles
Scaling factor:	Calculation required to fulfill the functional unit: • Aircraft 1 — 1/135 • Aircraft 2 — 1/525
Input/output flows for fuel allocation:	Amount of fuel required to fulfill the functional unit: • Aircraft 1 — 370.37 litres per FU • Aircraft 2— 190.48 litres per FU Amount of tailpipe emissions required to fulfill the FU • Aircraft 1 — 936.30 kg of CO_2 per FU • Aircraft 2— 481.53 kg of CO_2 per FU

3.2.4 System boundaries

For aerospace applications, system boundaries are typically defined based on the specific goals of the study, the available data, and where in the supply chain the product resides. In LCAs, defining the system boundaries is a crucial step in defining the scope of the assessment. The system boundary provides a visualization of the activities that are included in the study and for which data will need to be collected, and the environmental impacts calculated.

If only the operations of the reporting company are considered, this is called a gate-to-gate analysis. However, for most aerospace products, some if not most upstream activities will be included in the LCA in what is known as a cradle-to-gate analysis, which also includes downstream activities reaching the products end-of-life Cradle-to-gate analysis is the preferred analysis as it provides a more complete understanding of a products environmental impact throughout its lifecycle.

Cradle-to-grave is preferred for aerospace systems and subsystems that require significant design steps and that might benefit for a full lifecycle perspective when making design choices. It allows for supply chain stakeholder to understand the full environmental impact of their product.

However, a cradle-to-grave analysis in a complex value chain requires a set of common assumptions for the use and disposal phase. Use of common reference data precludes the use of primary data per operator but ensures consistency across the supply chain.

A summary of the system boundary options depending on the use case and goal is outlined in Table 4 below and can serve as quick reference. A visual guide to the different boundaries can be found in *Figure 6* and Figure 7.

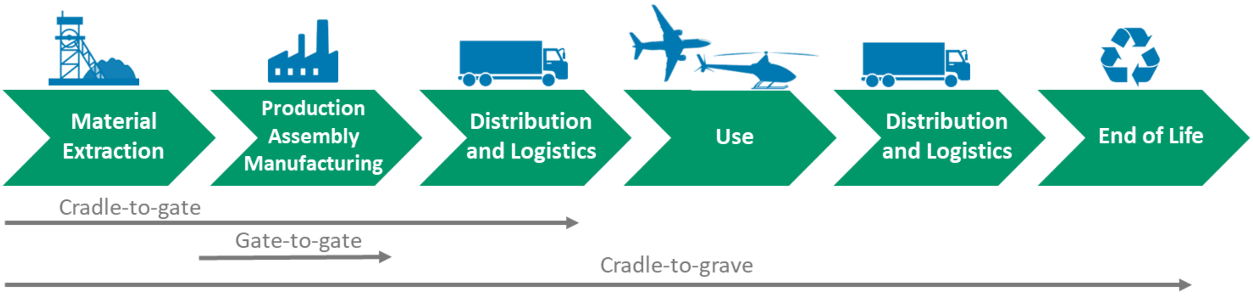


Figure 6. Illustration of system boundaries

Table 4. Summary of LCA boundary options

System boundary	Description	Recommended use based on study goal
Cradle-to-gate	Covers the lifecycle from raw material extraction to the point where the product leaves the factory gate	Use to evaluate manufacturing processes, comparing material choices, or focus on the environmental impacts of production and material sourcing
Gate-to-gate	Focuses on specific processes or operations within the production system	Use for assessing improvements or efficiencies within a specific production phase, such as component production or assembly processes, without considering upstream or downstream impacts
Gate-to-grave	Considers only the use and disposal phases, starting from when the product is delivered to the customer	Use to isolate operational impacts (e.g., fuel consumption, maintenance) and end-of-life considerations without accounting for production impacts
Cradle-to-grave	Includes the full lifecycle from raw material extraction to final disposal	Use for holistic assessments of environmental impacts across all phases of an aerospace product's life, particularly for sustainability strategies or regulatory compliance
Cradle-to-cradle	Includes the full lifecycle from raw material extraction through the circulation of end-of-life products and materials back into the system at their highest values	Use to evaluate product circularity and the effect of reducing waste, reusing materials, and regenerating nature. See IAEG WG14 for more information on the Circular Economy in Aerospace.

The scope of an LCA in terms of lifecycle stages covered will depend on the overall purpose of the LCA and the specific use case as per Table 4.

However, as a general answer for aerospace products the recommendation on scope is: Activities performed by the reporting company associated with the production of the product, and purchased electricity, steam, heating and cooling for use of that production should be included (gate-to-gate). Exclusion of specific upstream and downstream activities, if necessary, should meet the cut off criteria outlined in section 3.2.5 depending on the use case targeted and purpose of the LCA.

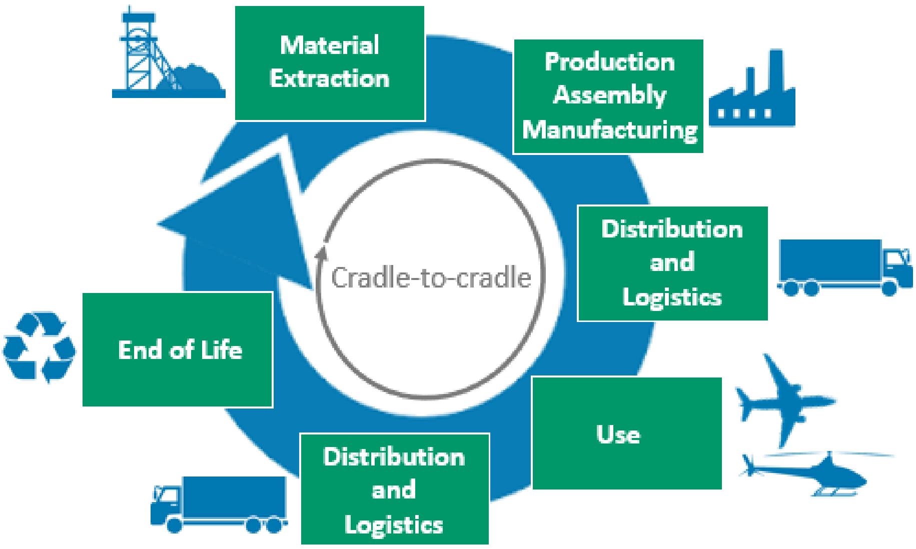


Figure 7. Cradle-to-cradle system boundary for a circular product lifecycle

3.2.5 Exclusion Criteria

The criteria to exclude certain parts of the LCA are intended to aid LCA development and data collection. The use of any cut-off should be avoided as it introduces gaps in data. Any available data should be included into the LCA as cut off rules are not to be used to “hide” data. If no primary data is available, secondary data or allocation methods should be used. It is appropriate to use cut off rules only when the data is unavailable, and no other assumption or allocation can be made.

The default cut off rule is 5% per life stage, meaning that each lifecycle stage or module should be 95% covered using LCI data[9]. Any use of cut off rule in processes should be clearly outlined in the report with all the other assumptions used.

As upstream phase involves data collection from suppliers, additional rules are implemented to facilitate the data gathering. The energy and water consumption and waste generation from sub-tier-1 suppliers should be collected if the sub tier supplier provides more than 20% wt/wt (weight ratio) of the total assembly. If the supplier has several facilities which manufacture different parts, the 20% wt/wt rule applies [10].

In addition, the following processes, and other common exclusions, may be excluded from the LCA:

- Infrastructure and equipment lifecycle and maintenance
- Research and development activities
- Packaging upstream and downstream outside of direct control
- Transportation of raw and basic materials to the manufacturer’s site

3.2.6 Modelling Approaches

A model of the system should be developed once the LCA scope and functional unit is decided. The product, component or system model should include the following elements:

- Bill of Materials (BoM) or other relevant data
- A system boundary (flow diagram) covering the entire lifecycle and the different actors
- All assumptions related to transportation systems
- All assumptions related to use scenario (if relevant)
- Assumptions related to End-of-Life (EoL) scenario, including recycling and recovery as relevant

Modelling should be established at a level where it enables a meaningful comparison between products delivering the same function. The model used in an aerospace LCA should:

- Quantify all impact categories and identify the most relevant ones, lifecycle stages, processes and direct elementary flows
- Facilitate the comparison between products that fall within the same function or application
- Calculate benchmarks against a representative product or system if one is available
- Define the classes of performance (if appropriate)

The LCA should detail all the steps taken to define the representative product or system model(s) in the study and report the information gathered while preserving the confidentiality of data if required. Any data gathered during the LCA considered confidential in nature (due to competitive business aspects, intellectual property rights or similar legal restrictions) shall not be made public under any circumstances. Models developed should be presented and discussed with the relevant stakeholders.

3.2.6.1 Hierarchical LCA Approach

Part of the definition of the representative product and system flow is to define the hierarchical organization of the reference flows that converge into the final product. When the system boundary is defined including upstream and downstream activities, and there are multiple supply chain companies involved in providing relevant data to an LCA and agreement on the boundaries of each analysis is needed upfront and a system boundary flow diagram with the different actors helps clarify the flow of information across organizational boundaries.

Carrying out cradle-to-grave LCAs in a hierarchical supply chain where subcomponents build into components and then subsystems, and systems lead to a full vehicle means that the scoping approach has to be defined upfront. Subsystem and component manufacturers can provide cradle-to-gate results to the next more complex integrator party (Subcomponent to component, component to subsystem, subsystem to system etc.) and then carry out the gate-to-grave portion themselves based on common assumptions; or each component manufacturer of an upfront defined size and complexity might carry out the full cradle to grave analysis and provide those results to the integrator based on a set of common assumptions and agreed output format and granularity

In the first case, the integrator is free to carry out the cradle to grave analysis of the final product both with the reference data used by their suppliers and with more specific proprietary data if available. However, both should be developed and the results clearly marked to ensure the reference data gate-to-grave analysis is consistent with the rest of the value chain. In the second case, if the integrator does not wish to carry out the analysis based on reference data (or reference data for the use and end-of-life phases of their system doesn't exist), it would be their responsibility to provide appropriate data to their suppliers to carry out the hierarchical LCA.

Regardless of the hierarchical structure and specific organizational boundaries, supply chain partners and final product integrators should use the same set of assumptions for the use and end of life phases to avoid confusion on components and final product using different assumptions. Those assumptions might be based on reference use and end-of-life assumptions for the product to avoid proprietary hurdles and to standardize assumptions or might be based on specific use and end-of-life assumptions. These specifics should be declared as part of the LCA if different from the established references. Some examples of assumptions and methods that can be used across the aerospace industry or for specific products are included in the following sections.

3.2.6.2 Use Phase Method and Reference Data

This section focuses on commercial aviation, details for other aerospace products are not included in this version of the aerospace framework but might be expanded upon in the future.

Fuel consumption is the largest contributor to lifecycle emissions for aerospace products and it varies depending on aerospace vehicle size, efficiency, payload and mission. The LCA approach recommended by IAEG WG12 is consistent with that recommended for GHG emissions accounting in IAEG WG3 in their guidance for Scope 3 category 11 emissions[11] where fuel burn estimates are recommended to be declared in block fuel format (per FH or km) for reference aircraft/aerospace vehicle sizes and mission ranges based on basic mission profiles.

Declaring which reference aircraft and mission is considered should be required as part of an aerospace LCA. Mission assumptions (weight range, cruise altitude, speed, engine settings) should be used and declared up front along with the reference. Other utilization factors (flight hours, number of missions/km covered), and vehicle expected lifetime should also be declared as part of the LCA.

See the IAEG document Guidance for Calculating Aviation Scope 3 Emissions: Category 11 – Use of Sold Products[11] sections 6.2 and 7 for some examples of reference aircraft and mission data to be included, this data follows the reference documentation from IAEG WG3. Other examples are present in existing aerospace PCR[10].

3.2.6.3 End-of-life Methods

End-of-life stage starts at the decommissioning of an aerospace product and covers the activities of transportation to the treatment location and treatments until the final disposal (recycling, incineration with or without energy recovery, landfill). Different materials are often treated differently at the end-of-life. Obtaining primary data on waste streams can be challenging, especially when dealing with global supply chains and diverse dismantling regions. In such cases, it is common practice to use global averages for common waste streams to allow for environmental impacts assessment.

Figure 8 illustrates a few examples of waste streams global averages for materials commonly used in aerospace industry.

Using global averages provides a reasonable estimate and can significantly aid in evaluating the environmental impacts of aerospace components at their end-of-life phase. However, it remains essential to declare the use of these global averages to maintain transparency and accuracy in environmental impact assessment.

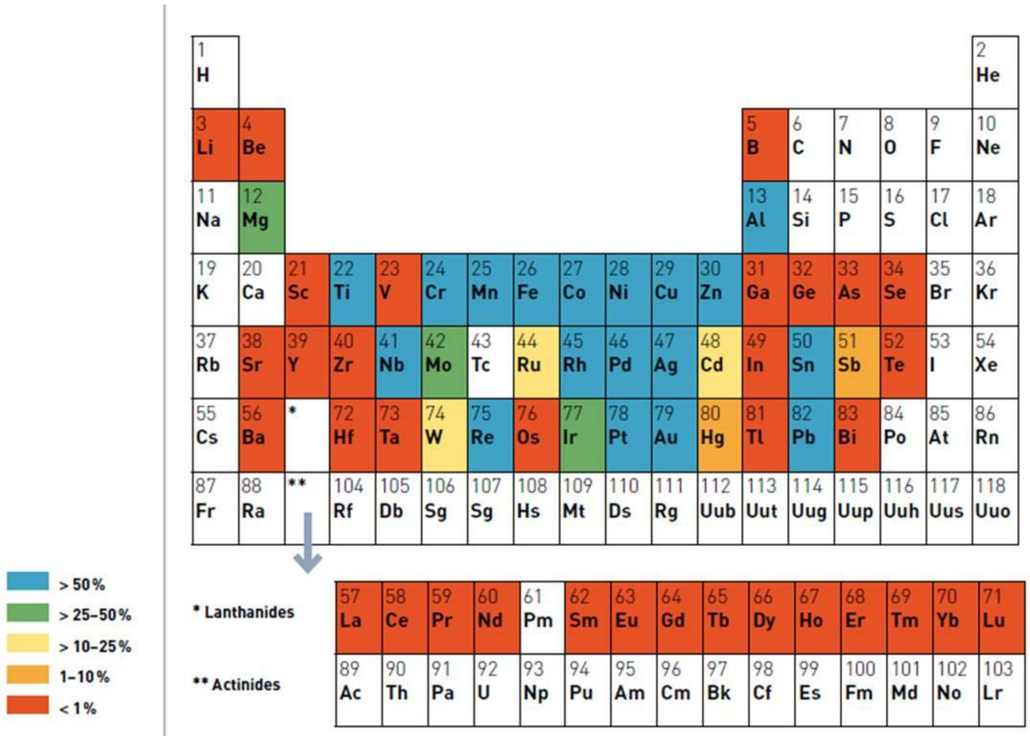


Figure 4. EOL-RR for sixty metals: The periodic table of global average end-of-life (post-consumer) functional recycling (EOL-RR) for sixty metals. Functional recycling is recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use. Unfilled boxes indicate that no data or estimates are available, or that the element was not addressed as part of this study. These evaluations do not consider metal emissions from coal power plants.

Figure 8. Illustration of global average recycling rate for some metals[15]

It is also important to note that these global averages may differ, depending on material features and characteristics from recycled material rates that may be used for input raw materials. Note that properties of the recycled material may not be compliant with the high standards of aerospace materials (e.g.: titanium, carbon fiber composites) depending on the intended use.

End-of-life and material use are interrelated through a circular perspective. In the LCA practice, the burdens and benefits allocation between recycling of materials and use of recycled content should be clearly stated. Indeed, this choice will affect the results and the associated interpretation. Several methods exist to consider the relationship between recycling and recycled material use and avoid double-counting in the context of a circular economy and doing an LCA on the second life of a material. Main ones include:

- The **Cut-off method** (also called Stocks method or 100:0): This method follows the “polluter pays” principle. It allocates 100% of the burden from the primary production of materials to the primary user. If the material is recycled at the end-of-life stage, the primary user does not receive any credit.

The recyclable material is thus available “burden free” to recycling processes and resulting recycled material bears only the impacts of the recycling processes when used by the secondary user.

- The **Avoid Burden method** (also called Closed Loop method or 0:100): This method assumes that a recycled material replaces a quantity of virgin material in the secondary lifecycle. The burden of recycling process and the benefits of avoided virgin material are credited to the primary user.

- The **Shared Burden method** (examples: 50:50 and Circular Footprint Formula) This method is based on shared burden between primary and secondary user. The allocation between primary and secondary user can be variable as illustrated in the following examples.

- 50:50 allocation: This method allocates 50% of the burdens to each user
- Circular Footprint Formula: This method has been developed by the European Commission to serve PEF and OEF framework. Depending on the supply and demand of the recycled material, the burdens of recycling are divided between the primary system and secondary system. Within the PEF guidance, this is referred to as “the A factor”, where an A factor of 1 would reflect the 100:0 approach, and an A factor of 0 would reflect the 0:100 approach. For PEF studies, the A factor will always fall within the range of 0,2 – 0,8. A value of 0,2 indicates a low supply of recyclable materials and high market demand, while 0,8 indicates a high supply of recyclable materials and a low market demand. Specific values are provided for PEF studies, but if none are available, a default value of 0,5 is used.

The cut-off method is the easiest to use and is recommended unless another method is mandated by the LCA stated goal or use case.

3.3 Inventory Analysis

The inventory analysis stage involves the compilation and quantification of inputs and outputs entering and leaving the system of interest. The aggregated inputs and outputs of all scaled processes of a product system represent the lifecycle inventory (LCI), and account for and quantify all relevant interactions between a product system and the natural environment. When compiling the lifecycle inventory, several choices need to be made regarding data selection, associated data quality, cut-off criteria, and allocation methodology. IAEG WG12 has a series of recommendations to support LCA studies modeling aerospace product systems.

An LCA model consists of a network of interconnected unit processes that collectively deliver the study functional unit. Each unit process represents a discrete step in the product lifecycle, transforming specific inputs into outputs as shown in *Figure 9* below.

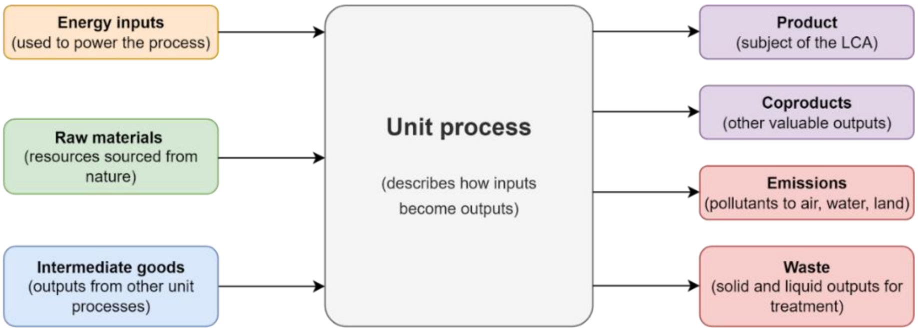


Figure 9. Structure of a unit process used in LCA studies, with physical and energy input flows and product and pollutant output flows. Credit: Yordas

3.3.1 Data Types and Sources

Data involved in an LCA is typically categorized into two types: primary data and secondary data.

- Primary data refers to the quantified values of processes or activities obtained through direct measurement or calculations based on these measurements. This type of data is often collected from real-world operations, such as manufacturing processes, and is essential for capturing accurate, context-specific environmental impacts
- Secondary data refers to data obtained from sources other than primary data. These include established LCA databases, industry reports, and peer-reviewed literature. Secondary data is used when primary data is unavailable or impractical to collect and provides a broader inventory of environmental information.

Table 5 below offers an overview of some of the data types commonly found across aerospace LCAs and some example data sources to illustrate the varied nature and origin of the data used in LCAs

Table 5. Common data type examples found in an LCA and their sources

Data type	**Description**	**Example data sources**
Unit Processes involved and Production sequence	An understanding of each process step in the system of interest such as shaping, forming, finishes, assembly, and inspection.	• *Specifications and part drawings* • *Site maps* • *Process flow diagrams* • *Production schedules* • *Quality Management Systems (QMS)*
Raw materials & components	The names and quantities of all materials used in the system such as metals, composites, electronic components, and hazardous chemicals.	• *Bill of Materials* • *Purchase orders* • *Safety Data Sheets (SDS)* • *Environmental Management Systems (EMS)* • *See IAEG Work Group 3 for purchased good and services guidance*

Energy consumption	Details of the quantity of energy consumed and the source of energy such as monthly or yearly electricity consumption per monthly or yearly product delivered.	• *Utility bills* • *Equipment readings* • *Site level utilities* • *Factory/building level utilities* • *Machine plate ratings and time studies/ production schedules*
Transportation details	Information relating to the movement of materials used in the system including rail, truck, maritime shipping, or air transport.	• *Suppliers for locations, modes of transport, fuel types* • *Web mapping platforms (like google maps) for distances*
In-process waste and emissions	Details of manufacturing waste produced such as metal shavings, hazardous waste, contact materials (tape, rags, temporary protective materials), volatile or fluid waste.	• *Solid waste and hazardous waste teams* • *Environmental Management Systems (EMS)* • *Reporting teams* • *Testing results*
Co-production	Identification of co-products (other marketable products) produced	• *Site maps* • *Process flow diagrams* • *Sales orders*
Product use	Data relating to typical usage patterns, power usage or maintenance requirements	• *Product Maintenance Manuals and design specifications* • *See IAEG Work Group 3 for product use guidance*
End-of-life disposal	Information on what happens to the product at the end of its useful life such as refurbishment, landfilling, recycling or incineration.	• *Customer surveys* • *Government publications* • *Waste regulations*

3.3.2 Reference Data Gaps

Addressing data gaps in current aerospace LCA databases is essential for enhancing the accuracy and reliability of environmental assessments. This section outlines tactical approaches to expand existing databases, focusing on areas where coverage is limited for significant aerospace materials, industrial activities, and processes.

Databases for General and Aerospace-Specific Data

Several database providers offer comprehensive LCA datasets that are widely utilized among IAEG members. Notable sources include:

- **Sphera**: Renowned for its extensive LCA databases, Sphera provides detailed data on materials and processes relevant to various industries, including aerospace.
- **Ecoinvent**: One of the most comprehensive LCA databases available, Ecoinvent offers high-quality data on a wide range of materials and processes, including those specific to aerospace.
- **NASA Open Data Portal**: This portal provides access to a vast array of datasets related to aerospace and other scientific fields.
- **Federal Aviation Administration (FAA) Data & Statistics**: Offers data on various aspects of aviation, including operational metrics and environmental impacts.
- **USC Aerospace Database**: Includes records from periodicals, conference papers, trade journals, and technical reports, covering all aspects of applied research in aerospace.

Some initial gaps in the reference data available for aerospace materials and processes have been identified by aerospace LCA practitioners. IAEG WG12 will continue to assess and address those gaps in existing databases through collaboration with database providers and understanding where the group should facilitate the creation or expansion of more aerospace-focused databases

The group will explore options for expanding existing databases to better represent aerospace materials and processes, particularly in areas where coverage is limited. This includes significant aerospace materials, industrial activities, and processes in various geographical contexts. Enhancing the breadth and depth of available data will improve the accuracy and reliability of LCAs in the aerospace sector.

3.3.3 Out of sector datasets

The aerospace industry requires a standardized approach to key out of sector data in Life Cycle Assessments (LCAs) to ensure consistency, accuracy, and comparability of results. The most important out of sector dataset used in an aerospace LCA is the well-to-wake environmental impact of the fuel used by the aerospace end product.

3.3.3.1 Fuel

This section outlines a proposed framework for incorporating fuel data into LCAs, emphasizing the use of global average datasets and guidelines for supplementing these with region-specific or primary data.

<u>First recommendation:</u>

This framework document recommends the use of a global average factors for fuel-related secondary data. This approach ensures a baseline level of consistency across different LCA studies, facilitating comparability and benchmarking.

Utilizing a global average dataset helps to standardize the environmental impact assessments of fuels used in aerospace applications. It accounts for the average emissions and energy consumption associated with fuel production, refining, and distribution on a global scale. This is especially important for the aerospace sector as through their lifecycle, aerospace products are likely to utilize fuels from many different countries and regions as their operating model and ownership changes.

Second recommendation:

Assume commercial aircraft are using conventional Jet A1 fuel to calculate their environmental impact wherever possible. Jet A1 has a well-documented refinement process and datasets covering worldwide production of Jet A1 are available in the databases mentioned in 3.3.2

This approach excludes the impact of Sustainable Aviation Fuels in reducing the environmental impact of aviation. Sustainable Aviation Fuels are an emerging class of fuels that could significantly reduce the impact of aviation on the environment, particularly on the realm of GHG emissions. However, there are multiple industrial pathways to produce SAF, and many different feedstocks which impact their well-to-wake environmental impact. Though initial LCA studies are being carried out for some of the SAF pathways in certain regions there is currently not a sufficiently mature dataset on SAF production and combustion in the databases previously mentioned.

Third Recommendation:

If studying the impacts of SAF on an aerospace product is particularly relevant for the case study, and therefore it cannot be excluded the recommendation from this document is to include a detailed study including primary data of the SAF sourced, its feedstock nature and location (including land use impacts of the feedstock) and the process used to generate it as well as the intended blend ratio and availability throughout the products lifecycle.

Another option is to limit the study to the impact of SAF on GHG emissions as the only midpoint considered and use well -established models such as the GREET model from Argonne Labs or the CORSIA impact factors provided by ICAO (Section 3.3.1 of ICAO Annex 16, Volume IV, CORSIA, 1st edition, 2018) which are used in GHG emissions accounting methods. In addition to the emissions impact models, an estimation of the availability of the SAF during the products lifecycle may be made available aligned with well-known prediction scenarios such as the International Energy Agency (IEA) Sustainable Development Scenario. If this approach is taken, this section of the LCA should be highlighted as only showing limited environmental impacts and a comparative study to the Jet A1 only option should be carried out to highlight the variability added by the SAF assumptions. This will help mitigate the potential uncertainty introduced by the SAF forecasts.

Improving fuel datasets:

As discussed in the previous section on aerospace databases (3.3.2) it is important to continue to improve existing data on the aerospace sector in the LCA databases. One aspect of this is to continue to improve the aviation fuel datasets to include regional differences and operator data to be able to carry out more granular studies for aerospace products intended for specific regions and operating models which can significantly impact the LCA results compared to global averages.

Collecting data specific to different geographical regions can account for variations in:

- **Energy Mix**: The proportion of renewable versus non-renewable energy sources used in fuel production.
- **Production Technologies**: Differences in refining and production technologies that affect emissions and energy efficiency.
- **Regulatory Standards**: Local environmental regulations and standards that influence fuel production and usage practices.

- **Primary Data**: Where possible, primary data shall be collected directly from fuel suppliers and aerospace operators. This includes:
- **Fuel Composition**: Detailed chemical composition of the fuels used.
- **Operational Data**: Real-world data on fuel consumption and emissions during aircraft operations.
- **Supply Chain Data**: Information on the logistics and transportation of fuels from production sites to end-users.

Collecting this information can help improve existing datasets and improve the specificity of the LCA, however, until this data is more widely available and collected the recommendation remains to use global fuel data in order to reduce unwanted variability in LCA results and account for global nature of aerospace value chains.

3.3.3.2 Transport, electricity, steam, heating

In addition to fuel, there are other relevant out of sector datasets used in an aerospace LCA. Most relevantly data around transport legs, and the electricity mix in each region as well as the environmental factors of steam, natural gas and other utilities used in the production phases.

The recommendation in this document is that datasets for purchased electricity, steam, heating and cooling for use of product production are to be region specific rather than global wherever the information is available in the databases outlined in section 3.3.2. In most recognized LCA databases there are enough details and coverage in the grid mix to recommend their usage, if the region of production is within the coverage. If there are specific on-site green electricity installations or green electricity contracts in the production plants, primary data is recommended to capture their benefits over the regional grid.

Other datasets, such as average transport emissions, utilize the global averages present in the well-known databases unless primary data is available. Any detail added to the transport sections in the future might be tied to the wider effort in expanding databases with aerospace data rather than included in a specific recommendation in the framework document.

3.3.4 Data quality

Data quality is the characteristics of data that relate to their ability to satisfy stated requirements (ISO 14040:2006). Data quality covers various aspects, such as technological, geographical and time-related representativeness, as well as completeness and precision of the inventory data. WG12 framework recommends basic principles for data quality on LCAs basic transparency guidelines to declare data quality attributes for the most relevant quality indicators. Specific requirements depend on the goal and scope of the study and are left open for to the study commissioner to determine.

Technological Representativeness is the degree to which the data reflect the actual technolog(ies) used in the process. Examples of characteristics to declare for this attribute include “exact technology”, “similar technology based on secondary data”, “different technology than those included in the scope of the study”, or “unknown technology”.

Geographical Representativeness is the degree to which the data reflects actual geographic location of the processes within the inventory boundary (e.g., country or site). Examples of characteristics to declare for this attribute include “exact country or country subdivision the process takes place”, “Same region or subregion", "Global", or "location of the process is unknown". It is recommended to use global values rather than data from a region different from where the activity is located. Deviation from this recommendation should be declared and a justification provided.

Temporal Representativeness is the degree to which the data reflect the actual time (e.g., year) or age of the process. Examples of characteristics to declare for this attribute is "Data is from reporting year", "Data is less than 5 years old", "Data more than 5 years old", or "age of data is unknown". Data older than 5 years may not be used unless: (1) data series over time is needed and therefore a longer period of data collection is needed; Or (2) a primary and relevant data point exists older than the 5 years without an existing replacement of more accuracy. Any of these variations should be declared as part of the data transparency.

Completeness is the degree to which the data are statistically representative of the process sites. Examples of characteristics to declare for this attribute include "All relevant sites for specified period", "< 50% of sites for specified period", "> 50% of sites for shorter period", "less than 50% of sites for shorter time- period", or "unknown". Any exclusion of data by the application of the cut-off criteria must also be declared. See Section 3.2.5 for cut-off criteria.

Finally, **Reliability** is the degree to which the sources, data collection methods, and verification procedures used to obtain the data are dependable. Examples of characteristics to declare for this attribute include "Measured activity", "measured and externally verified", "activity data partly based on assumption", "Calculated value", "literature value", "qualified estimate", "non-qualified estimate", or "unknown".

Primary data, data measured by the reporting company, is required when it pertains to parameters within the issuing company's direct control and aligned with a company's existing reporting commitments. Standardized secondary data can be used for activities that do not meet the cut-off criteria, or where primary data is not available or assessed to be less representative than secondary data. See Section 3.2.5 for cut-off criteria.

If representative data or assumptions are needed to enable product comparisons or to enable hierarchical LCA build up, then use of non-primary data should be declared.

Standardized secondary data such as that pertaining to direct emissions from combusting fuels, and emissions associated with electricity productions may follow the data quality boundaries and should declare the parameters outlined above.

Declarations of the attributes or characteristics of the data quality are important to understand the reliability of the study results and properly interpret the outcome of the study and must be provided regardless of which data quality requirements apply to the study. The intent of providing this information is to provide full transparency of the data used and allow users of the study results to determine if the data meets their needs and requirements. All these recommendations are summarized in Table 6.

Table 6.Summary of Data Quality recommendations

General	Attributes of data quality must be declared regardless of data quality requirements applied to the study
Technological Representativeness	Aerospace specific activity data is preferred
Geographical Representativeness	Use global values rather than data from a region different from where the activity is located.
Temporal Representativeness	Data older than 5 years may not be used unless: (1) data series over time is needed and therefore a longer period of data collection is needed; Or (2) a primary and relevant data point exists older than the 5 years without an existing replacement of more accuracy.
Completeness	Any exclusion of data by the application of the cut-off criteria must be declared. See Section 3.2.5 for Cut-off criteria.
Reliability	Primary data is required when it pertains to parameters within the issuing company's direct control and aligned with a company's existing reporting commitments. Standardized secondary data can be used for activities that do not meet the cut-off criteria, or where primary data is not available or assessed to be less representative than secondary data. See Section 3.2.5 for Cut-off criteria.

In addition to these basic recommendations, it is also possible to quantify data quality, data quality rating (DQR), and thus define comparability between different studies or threshold values as minimum requirements within a company. There are several methods for doing this, all of which include the same mentioned indicators but have a different numerical scale. A deep insight into the methods is provided in the ILCD handbook [8], Catena-X guideline[13] or from Ecoinvent[14].

It is up to the study commissioner or the company itself to decide whether and which data quality rating is chosen. However, data quality is to be quantified first at the dataset level. The overall assessment of the data quality of the study for each impact category assessed may then be calculated as a weighted average, using the contribution of the specific impact category as the weight.

The advantage of this is that it quickly becomes clear which, if any, process data may have a relevant influence on the data quality and thus on the outcome of the study. If the data quality is not quantified, a sensitivity analysis can be used to estimate the impact of process data whose data quality has been classified as poor on the overall result.

Moreover, certain methodologies employ numerical data quality ratings (DQR) for uncertainty assessments to determine the fluctuation range. However, this approach is very complex and requires appropriate tools and in-depth training. In any case, if a process / data contributes significantly to the final results, but the data quality is poor, this would influence the conclusion quality and reliability. In that case, more work may be done in order to improve the quality of the data.

3.3.4.1 Data Quality on Upstream processes

The raw and materials (Structure, systems, Interiors) data composing the aircraft collected directly from the OEM internal database or from suppliers and sub-tiers, are compiled following a manual or automatic (digitalized process) as defined up front when structuring a hierarchical LCA. However, this data from multiple sources might require a check on consistency (units, parametrization) and data quality and some iterations before it will be uploaded into the LCA tool model, for processing of Environmental impacts. This can be improved in subsequent LCAs carried out with the same partners with more and more of the consistency issues eliminated as the boundaries are better defined.

3.3.5 Allocations rules

Allocation occurs when a process or system generates multiple outputs (co-products), requiring the distribution of environmental impacts among them. There are several allocation methods including economic allocation, mass allocation, energy content allocation, and system expansion. Each method has specific assumptions and limitations, and the choice of approach can significantly affect the outcomes of an LCA. Therefore, selecting the appropriate allocation method is vital to ensure that the LCA accurately reflects the environmental performance of a product or process.

As LCA aims to quantify the impacts associated with a discrete product system, it is necessary to differentiate the impact of co-products arising from multi-functional processes. Where processes are multifunctional, the process for solving the issue must be conducted in accordance with the ISO 14044:2006 LCA standard, which provides the following four-step hierarchy:

1. **Avoid allocation by subdividing systems –** allocation should be avoided by dividing the process into sub-processes
2. **Avoid allocation by system expansion** – the system boundaries are expanded to include the additional functions related to the co-products
3. **Allocation by physical relationships** – the inputs and outputs of the system are partitioned between its different products or functions in a way that reflects the underlying physical relationships between them (e.g., mass, energy).
4. **Allocation by non-physical relationships –** the inputs and outputs of the system are partitioned between its different products or functions in a way that reflects a non-physical relationship (e.g., market value).

Examples of where and how allocation occurs across aerospace LCAs are included below, with an emphasis of using physical relationships where possible.

Allocation per lifecycle phase

During the upstream phase mass allocation is recommended, and if not possible then the number of parts can be used as allocation criteria. When completing allocation for a manufacturing site, the number of aircraft to be produced and number of parts for the specific product can be used.

Allocation Based on Material

The environmental impact of certain aircraft parts will have a higher environmental impact than other parts. Some of these parts include electronics and composites. Whereas metallic components typically have a lower environmental impact. This is why it is recommended to use part allocation for electronic and composite components. Whereas mass allocation is recommended for the remaining aircraft components.

3.4 Impact categories and calculations

In the pursuit of sustainability within the aerospace industry, it is imperative to adopt standardized methodologies for assessing environmental impacts. This sub-section outlines the recommended approach for categorizing and calculating impacts during an LCA addressing common queries that practitioners may encounter.

3.4.1 Integrating Lifecycle Impact Assessment (LCIA) Methods

This sub-section provides an Overview of the most commonly used LCIA Methods within the aerospace sector (non-exhaustive list):

- **TRACI[6]:** Developed by the United States Environmental Protection Agency. It is widely used in North America with a focus on regional impacts. TRACI employs a midpoint approach for normalization and weighting processes, as the methodology's structure does not yet support integration of endpoint modeling. It evaluates seven primary impact categories, alongside multiple subcategories specifically focused on human health effects.
- **CML[4]:** Developed by the University of Leiden in the Netherlands in 2001 and updated in 2016, this methodology features an extensive array of characterization factors. It supports normalization across all interventions and impact categories, accommodating different spatial and temporal levels. Widely adopted by industries, it is recognized and utilized on a global scale.
- **ILCD[8]:** Developed by the European Commission, the ILCD offers a comprehensive framework for evaluating environmental impacts at both midpoint and endpoint levels. The recommended characterization models are categorized by quality, facilitating transparent evaluations.
- **EF[5]:** Developed by the European Commission, the EF (Environmental Footprint) impact assessment method evaluates 16 impact categories to address a broad range of environmental issues. The method includes normalization and weighting steps, which are mandatory for Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) studies—LCA-based approaches recommended by the EU.
- **ReCiPe[4]:** Developed in 2008, with the latest version being ReciPe2016, ReCiPe is a widely used LCIA method that can calculate 17 midpoint indicators and 3 endpoint indicators. The method also offers characterization factors based on three cultural perspectives to provide flexibility for practitioners.

Given its comprehensive and relevant list of environmental impact categories for the aerospace industry, as well as its endorsement by the EU, IAEG WG12 recommends the EF LCIA method for use in conducting LCAs within aerospace. Final choice of method is a voluntary and unilateral decision of each company.

3.4.2 Midpoint Indicators for Detailed Assessment

Focusing on midpoints offers a detailed and comprehensive assessment of specific environmental impacts throughout the lifecycle. Midpoint indicators represent impacts at an intermediate stage of the cause-effect chain, such as greenhouse gas emissions or resource depletion. This approach reduces uncertainty compared to endpoint assessments and provides reliable results.

Although endpoint assessment simplifies interpretation and communication by reflecting the final effects on areas of protection like human health, ecosystem quality, and resource availability, it requires more work due to complex modelling and may result in a potential loss of detail.

Therefore, for a comprehensive and robust LCA, it is advisable to focus on midpoint indicators. This method provides detailed insights into specific processes and their contributions to environmental burdens, facilitating targeted improvements and ensuring a thorough and effective evaluation.

3.4.3 Comprehensive Impact Assessment: Broad to Focused

When initiating an LCA, the question often arises whether to consider a broad range of impact categories or to focus on a select few. The recommended approach is to start with a comprehensive list of potential impacts.

Starting with many impacts ensures a comprehensive and robust assessment, addressing all potential regulatory requirements and stakeholder concerns. Once initial results are obtained, focusing further analysis and communication on fewer, significant impacts simplifies the LCA process, making results more relevant, easier to communicate, and provides better support for decision-makers.

The selection of impact categories to focus on depends on the scope of the study. The following list presents a general recommendation of impact categories that form the recommended baseline for an LCA of an aerospace flying product. This list was compiled through a review of relevant impact categories and direct input from aerospace companies, highlighting some of the most common environmental impacts for an aircraft LCA:

1. **Climate Change:** GHG emission reduction is a clear priority of the aerospace industry in support of the IATA commitment to Fly Net Zero by 2050.
2. **Resource Use (EF categories: Minerals and Metals & Fossils):** better understanding of resource use impacts can be used to build aerospace supply chains that are more sustainable and resilient and reduce the amount of natural resources used.
3. **Photochemical Ozone Formation (Summer Smog):** focus on this impact will help drive continued improvement of air quality at and around airports and reduce environmental impacts for those communities.
4. **Acidification:** reduction of sulfur oxides (SOx) and nitrous oxides (NOx) are an important part of overall aerospace and airline impact reduction.
5. **Particulate matter:** reduction in particulate matter emissions are an important part of overall aerospace and airline impact reduction both from an air quality and a cloud formation perspectives.

It is important to note that this list might vary depending on the aerospace product the LCA is for, and the intended objective of the LCA. For example, a study focused on the impact of different fuel mixes might also consider biodiversity and land use impacts.

4 TOOLS

4.1 Introduction to LCA tools

This sub-section provides an introduction to LCA tools. The primary objective is to assist IAEG members in their decision-making efforts by examining the capabilities and features of various LCA tools available in the market. Here, we define and explore streamlined and advanced LCA tools while providing compelling comparisons of key features among the most widely used tools.

Disclaimer! This section is not intended to endorse a particular LCA tool for use by aerospace companies, rather it intends to guide industry in finding the best solution for their organization. Final choice on tools is a voluntary and unilateral decision of each company.

4.2 Considerations for LCA Tool Selection

4.2.1 Basic considerations

When choosing an LCA tool, you need to be clear about your specific needs, resources, and the level of expertise of team members. To assist in this selection process, you may consider the following questions:

- **What do you intend to use LCA for?** You first need to be clear about what you intend to use LCA for. Will you use LCA to make product claims, support R&D efforts, or simply identify the most problematic areas? For organizations aiming for a quick, high-level overview, a straightforward tool may be appropriate. However, if your goal is to conduct in-depth and detailed analyses, investing in a more sophisticated tool will provide the extensive functionality needed to obtain meaningful insights.
- **Are there any specific data needs?** Many LCA tools include databases as part of the subscription cost with more sophisticated tools being compatible with a number of datasets that can be purchased separately. For example, some tools include databases with wide coverage (e.g., Ecoinvent) while others include databases for specific industries or products, such as chemical inventories or electronics. It is essential to understand whether these databases align with your specific needs.
- **Who will use the tool and how familiar with LCA are they?** Some tools are more user friendly than others. Those with limited LCA expertise will face a steep learning curve for more advanced tools when compared to other simplified solutions with guided workflows.
- **What is the budget?** Budget constraints can significantly impact tool selection. You need to consider subscription, database, and training costs when determining the overall investment costs.

There is no such thing as the ‘right’ tool for all LCAs as your choice will depend on your needs, preferences, and the depth of analysis required to achieve your study goals

4.2.2 Advanced vs. Streamlined LCA Solutions

Table 7 provides a comparison of Streamlined versus Advanced LCA tools. This classification captures the main differences in capability, complexity, and intended user base, providing clarity for organizations seeking tools aligned with their assessment needs.

Table 7. Comparison of streamlined and Advanced LCA tools

Criteria	Streamlined Tools	Advanced Tools
Typical cost of purchase	Lower	Higher
Typical software format	Web-based application	Desktop application
Ease of use	User friendly	Complex
Modelling flexibility	Limited	Highly customisable
Choice of LCIA methods	Limited	Comprehensive
Database coverage	Limited	Comprehensive
Access to training and support	Tool dependent	Tool dependent

Key aspects to consider when choosing an LCA tool

- **Cost of purchase:** how affordable is the tool, does it provide good value for money?
- **Ease of use/User friendliness:** has the tool got a user-friendly interface? Is it designed for LCA experts or is it accessible to all?
- **Database coverage:** does the tool include or support a variety of secondary databases? Are these databases aligned with your product's needs?
- **Lifecycle impact assessment (LCIA) compatibility:** which LCIA methods are supported by the tool? Is the tool focused on a carbon footprint, or does it allow for multi-impact assessments? Can you choose the LCIA characterization model (e.g., ReCiPe, IPCC, PEF)? Do you need to have access to multiple models?
- **Modelling flexibility:** does the tool allow for customization or include advanced modelling features, allowing users to build scenarios, adjust assumptions, or conduct sensitivity analysis? Do you need these advanced tools to support your LCA or wider sustainability goals?
- **Access to training and support:** what training and support does the software owner provide to users? Is there adequate documentation, tutorials, or direct technical support? How much support will your organization need to effectively adopt and use a tool?

Note: there is no such thing as the ‘right’ tool as this will depend on your needs, preferences, and the depth of analysis required to achieve your environmental goals!

4.3 Streamlined LCA Tools

Streamlined LCA tools are designed for rapid analysis and typically focus on specific indicators (such as carbon footprint), industries (e.g., construction), or LCA impact assessment models (e.g., IPCC AR6). These tools are often web-based, utilizing secondary databases and user-friendly interfaces to help users quickly evaluate products, making it easier for organizations to produce LCAs efficiently. Owing to their cost-effectiveness and ease of use, these tools are particularly suited for individuals (or organizations) with limited LCA expertise, those only seeking a high-level understanding of their products' environmental impacts, or those with limited budgets (e.g., SMEs). There are hundreds of streamlined LCA tools on the market, examples include: AllocNow, Earthster, Ecochain Mobius, Greenly, and LCA Calculator.

While streamlined tools are suitable for initial assessments, they often lack the features required for comprehensive or highly specific analyses, and thus may not be suitable for companies wanting to incorporate LCA results into research and development activities or make environmental claims.

4.4 Advanced LCA Tools

Advanced LCA tools are designed with comprehensive and complex analyses in mind. These tools allow users to create customized models and employ various Lifecycle Impact Assessment (LCIA) methods. However, the demands of manual data entry and the plethora of options available can be overwhelming, with subscription costs and time commitments often presenting significant barriers to entry for smaller organizations. Owing to the significant financial and time commitments, these tools are most suitable for organizations with experienced teams looking to invest long-term in their use as part of their ongoing sustainability efforts.

There are four Advanced LCA software options available on the market, each with unique strengths and limitations, as illustrated in the matrix in **Table 5.2.** SimaPro and LCA for Experts (LfE) are recognized as market leaders, widely used in both industry and academia. Furthermore, Sphera, the owners of the LfE software have a 'data on demand' service where users can request the development of new process datasets. OpenLCA serves as an open-source alternative that offers advanced modelling capabilities with no subscription fees. Lastly, Umberto has advanced modelling capabilities and good technical support, offering a balanced combination of features and usability for detailed analyses.

Table 8. Comparing the features of SimaPro, OpenLCA, LfE, and Umberto

Aspect	LfE (GaBi)	SimaPro	OpenLCA	Umberto
Software free to use	X	X	✓*	X
Software free trial period	30 days	30 days	(Not applicable)	14 days
Included database	Professional Core	Ecoinvent	(Not applicable)	Ecoinvent
Ecoinvent compatible database	✓	✓	✓	✓
LfE compatible databases	✓	X	X	X
BOM import capabilities	✓**	X	X	✓
Integration with CAD software	✓	X	X	✓

Generate EPDs from LCIA results	✓	✓	✓	✓(*)
Has a “data on demand” service	✓	X	X	X
Scenario analysis	✓	✓	✓	✓
Sensitivity and Monte Carlo analysis	✓	✓	✓(**)	✓(**)
Ability to create customised reports	✓	✓	✓	✓
Inventory and result export to Excel	✓***	✓	✓	✓

*** Many databases will need to be purchased separately: https://nexus.openlca.org/databases**
(*) Depends on the selected plan: https://www.ifu.com/umberto/plans-pricing/commercial/
**** An add-on tool for purchase separately to the LfE licence: https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/lca-bom-import/**
(**) Indirectly, via external tools
***** Limited compatibility with Excel compared to the other options**

4.5 Use of LCA Databases

The use of these LCA tools often imply the use of commercial databases, it should be noted that special attention may be paid to the associated End-User Licence Agreements that may include specific use restrictions, such as:

- Licensee not entitled to publish licensed environmental data,
- Licensee must not publish any data allowing reverse-engineering of back-calculation of environmental data.

These conditions must be considered when elaborating reports and communicating during the analysis.

4.6 Conclusion

Automatic screening tools have undoubtedly improved the accessibility of LCA to non-experts and the features of advanced software packages have proven invaluable for decision-makers. Screening tools provide users efficiency and advanced software solutions offer sophistication.

5 RESULTS

This sub-section provides recommendations on how to structure and present results in a transparent manner fit for LCAs within the aerospace industry.

The results presentation and communication will vary depending on the overall objective of the study and the intended audience.

5.1 Characterization, normalization, and weighting decisions

It is recommended to present the results calculated from section 3.4 as characterized midpoint indicators to maintain transparency and avoid the subjective biases and potential oversimplifications introduced by normalization and weighting.

While normalization and comparing results to typical environmental impacts can be valuable for educational and awareness purposes, results should still be presented using characterized midpoint indicators. As for weighting, ISO 14040 states that “there is no scientific basis for reducing LCA results to a single overall score or number, since weighting requires value choices.” In the aerospace industry, which often involves complex systems, precision is critical, and decisions rely heavily on objective data.

Introducing subjective value choices could thus lead to misguided decisions. If conducting an internal trade study with a single score approach, clear communication of the weighting factors is needed and a sensitivity study to those weighting factors would be beneficial. And this normalized and weighted score is recommended to be avoided if communicating outside the immediate company boundaries.

Characterized results provide a clear and direct representation of the environmental impacts associated with the processes and products being assessed. This transparency is beneficial for stakeholders who rely on accurate data to make informed decisions. Furthermore, the ISO 14044 states that "Weighting, shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public." By adhering to characterized results, assessments can be communicated more effectively among peers, promoting data sharing and collaboration within the industry.

5.2 Criteria for stakeholder integration

In addition to the main results in the form of characterized midpoint indicators, supplementary data, as discussed in Section 3.4, may be of interest to communicate to ensure the outputs of the LCA match the required inputs of the LCA for the next level in the supply chain. In order to facilitate such an integration (e.g. 1st Tier supplier to OEM), it is beneficial to establish a standardized LCA data interface format which supports a consistent and harmonized exchange of LCA Data between respective stakeholders.

The data interface format may either contain environmental raw data or all relevant environmental indicators depending on the need of the customer of the data. This data exchange format should cover the lifecycle stages for which the respective party is responsible. To ensure seamless data handover without discontinuities, the rules for this interface format must be harmonized, including boundary conditions, functional units, and metrics defined within this framework. Additionally, quality rules for information and data included in this interface document should be clear and well documented.

6 CRITICAL REVIEWS

6.1 Introduction

A critical review is a process intended to ensure consistency between an LCA and the principles and requirements of LCA standards and reference frameworks (as stated by [ISO 14040]). It is an essential step to guarantee the accuracy of the analysis conducted.

Depending on the goal and intended audience of the LCA, review types and requirements levels may differ as well as reviewers' number and profiles.

For the aerospace sector, especially given the high technicality of activities involved, it is recommended to integrate critical reviews as recommended by ISO 14040 and ISO 14044 standards into the LCA process.

6.2 Scope and type of review

The scope and type of critical review shall be defined in the scope phase of the LCA.

When aimed at communicating results outside the company (e.g. Type III declaration) and/or comparing products' environmental footprint, LCAs shall be verified by and independent verifier with bearing the required qualification

6.3 Reviewers

Depending on LCA goal and intended audience, reviewers' number and profiles may differ. In particular, when an LCA is intended for public disclosure or for comparative assertions, an independent third-party review committee is required. Critical review can be done by an internal/external expert or by a panel of interested parties.

6.3.1 LCAs not disclosed to the public

For LCAs that are not intended to be disclosed to the public, internal reviews are recommended to ensure LCA reliability & accuracy.

Internal reviewers should not be part of the LCA project team, and it is recommended that they be trained to critical reviews methodologies.

6.3.2 LCAs disclosed to the public

For LCAs that are meant to be made public, an external third-party review is mandated in the ISO:14040 standard.

In this context, internal reviews as in 6.3.1 are still recommended in order to ensure LCA quality & prepare for external review.

In the case of an LCA conducted for type III declaration (Environmental Product Declaration, in compliance with [ISO14025]), the analysis shall be verified by an independent verifier with required competencies (cf. list recommended by EPD program operator).

As an example, information on reviews, as well as a list of agreed verifiers is available at www.environdec.com

The reviewers should have appropriate knowledge of the aerospace sector and its specificities and have appropriate competencies on LCA principles & methodology.

However, few LCAs have been published in the aerospace sector. This results in a small number of external reviewers having a significant experience in that field.

If the reviewer is not knowledgeable with the aerospace sector additional effort will be required to prepare for the review.

If the end goal of the LCA is to make comparative assertions, ISO requires that a review is conducted by a panel of a minimum of three people, including a panel chair and two other interested parties. A critical review may be performed alongside the study (concurrently) or after the study has been completed.

6.4 Review report

The review statements and comments as well as responses provided to recommendations made should be included in the LCA report.

6.5 Conflict of interest

In order to prevent possible conflicts of interest between a consultant and the contracting company within the verification process, in the case where the LCA is performed by an external entity (consultant), the cost of the verification must be established and paid between the contracting company and the verifier, and any possible conflicts of interest avoided.

The verifier entity must be distinct from the contracting company and consultant performing the LCA.

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APPENDICES

Appendix A: LIFECYCLE ASSESSMENT 101

This framework document distills best practices used in aerospace today as recommended by IAEG WG12 members, and it dives into some detailed LCA topics and methodologies. This LCA 101 section has been created as a helpful broad overview for LCA newcomers to get up to speed with basic LCA nomenclature and concepts. Basic information about the LCA landscape, stakeholder groups and brief descriptions of LCA essentials are provided here as a starter pack. Some simplified explanations have been provided in this section as a way to start on learning about LCA.

A.1 Welcome to Lifecycle Assessment 101

Lifecycle Analysis (LCA), also known as Life Cycle Assessment, is a systematic approach used to evaluate, quantify and assimilate environmental impact associated with all stages of a product's life, from raw material extraction (cradle) through production, use, and disposal (grave).

A.2. Lifecycle Assessment Methodology

The LCA process is defined in the ISO14040 and ISO14044 standards and is divided into four key phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. This document contains a brief introduction of these phases to facilitate an initial learning of LCA principle but is not intended to replace the details of the standards.

The first phase, Goal and Scope Definition, sets the boundaries and objectives of the study. This stage defines what will be included in the analysis, such as specific environmental impacts (e.g., carbon footprint, water usage) and the lifecycle stages to be evaluated. In the second phase, Inventory Analysis, data is collected on energy use, raw materials, emissions, and waste for each stage of the product's lifecycle. The third phase, Impact Assessment, involves translating the data collected into environmental impacts using established methodologies. In LCA, the LCIA phase aims to understand and evaluate the magnitude of the potential environmental impacts of a system based on the information provided in the previous inventory analysis stage. For example, emissions of carbon dioxide can be quantified in terms of their contributions to climate change, acidification and ozone depletion; or Lithium batteries have significant impacts on global warming but also human toxicity, acidification, depletion of natural resources, ozone formation and depletion and freshwater toxicity and eutrophication. Finally, in the Interpretation phase, the results are analyzed, and recommendations are made to reduce the overall environmental impact of the product or process. This process can be iterative as the inventory analysis, impact assessment or the interpretation of results phases might determine that the goal and scope of the study should be changed to match the study objectives once some data has been gathered.

A.2.1 Goal and scope definition

Many stakeholder groups might be interested in an LCA study depending on what the objective of LCA study is.

Determining 'contributors' and 'recipients' early is essential so that requirements can be clearly identified to support the definition and goal statements of the LCA study. Drawing and sharing a stakeholder map can help align contributors to recognize recipient needs and related rules from day 1. For further detail of potential stakeholders and LCA uses – refer to Section 2: USE CASES.

A.2.1.1 LCA SCOPE

In conjunction with mapping the LCA goals to indicate intended recipients and involved organizations, diagrams indicating LCA scope and coverage are helpful. Understanding what parts of the product lifecycle will be included and who will participate in the data inventory for an LCA is key to have the right team ready to contribute to the LCA study

Some LCA boundary templates are available to support clear communication. At the initial stages of an LCA study creating and sharing a clear diagram with the LCA study contributors may help minimize unwanted variation and duplicated or conflicting work. These diagrams can represent a linear lifecycle (*Figure 1*) capturing a products end of life or move towards a circular lifecycle (*Figure 6*). However, the boundary of whether the LCA study include the second-life product or not needs to be clearly defined. More details of the possible system boundaries and their implications are detailed in the System boundaries sub-section.

A.2.1.2 LCA contributors

Once the scope of the study is defined, key data collection contributors can be transparently planned further by tabulating relevant roles in any contributing organization. Some examples of the roles of an LCA are detailed in the table below:

Table 9. Examples of data collection roles involved in LCAs

Product Manager or owner	Supply chain and procurement	Operations or process personnel	Environmental health and safety	Designers and researchers
Provide data about the product lifecycle such as the BoM, installation instructions, expected use, maintenance data and manuals	Provide data about the product upstream suppliers, logistics, packaging	Provide data on production and assembly processes such as production and scrap rates, energy usage, water and chemical usage	Provide data on emissions and waste streams	Provide data on possible scenarios for scenario analysis and design alternatives

A.2.2 Growing interest in LCA in aviation and potential overlaps

Understanding and quantifying the environmental impact of aerospace products and process and how they affect the environment allows the aviation industry to leverage the ongoing technological advances such as modernization of materials, fuels, flight profile management, aerodynamic efficiency and propulsion to minimize potential impacts. LCA is an important tool for quantification and can serve to prioritize and strategize on technological advancements while limiting unwanted consequences from focusing only on single impact reduction.

In addition, various forms of environmental regulation have been implemented and are anticipated to be implemented across different geographical regions. The global nature of the aerospace industry means a high degree of exposure to many of these regulations and therefore the industry needs to be prepared to comply with the most stringent of these regulations. LCA constitutes one of the tools available to comply with regulations requiring a quantified understanding of the environmental impacts of a particular product or process.

For example, an increasing number of regulations require or will require an accounting of the carbon footprint of a product. While LCAs generally provide a wider set of impact metrics, carbon footprint studies can be a subset of an LCA study focusing only on carbon dioxide emissions, or perhaps all GHG emissions.

It is not unusual for individuals working on emissions reporting at organizational level (GHG Protocol Corporate accounting and reporting standard), or on compliance with carbon disclosure regulations (CBAM, CSRD), or on material transparency compliance to also work on product lifecycle assessments. Early understanding of areas where there are overlaps and differences helps minimize unwanted variation.

For example, in corporate emissions accounting it is common to define company activities with the Scope 1,2,3 division presented in *Figure 10*, whereas in LCA product level studies they are generally referred as foreground and background systems with upstream and downstream activities

Figure 10. GHG Scope emissions illustration[12]

Appendix B: LCA Use-Cases

By integrating LCA into each stage of the lifecycle—from raw material extraction, manufacturing, and distribution to use, maintenance, and disposal—environmental considerations are systematically incorporated. This holistic approach not only helps in identifying potential environmental impacts early in the development process but also in making informed decisions that enhance the sustainability of the entire product or service lifecycle. The result is a more sustainable outcome that balances environmental, economic, and social factors throughout the product's or service's lifespan.

B.1 Innovation and Design Stage

B.1.1 Need or Opportunity Definition

This stage involves identifying and clearly defining a specific market need, problem or opportunity to which the product, system or service will respond. This step involves understanding the target audience and market conditions to ensure the project aligns with real-world demands. Consider environmental impacts as part of the need definition process. Evaluate if the new product or service could address environmental concerns or reduce negative impacts compared to existing solutions.

B.1.2 Ideation or Brainstorm Process

This stage involves engaging in creative thinking and brainstorming sessions to generate a diverse range of ideas and potential solutions. This step encourages open-mindedness and the exploration of various approaches without immediate judgment. Incorporate environmental considerations into the brainstorming sessions. Generate ideas that focus on sustainability, such as using renewable resources, minimizing waste, or reducing energy consumption.

B.1.3 Ideas Exploration, Conceptualization and Selection

This stage involves evaluating and exploring the feasibility of the generated ideas. Develop initial concepts, analyze their viability, and select the most promising ideas based on criteria such as innovation, practicality, and alignment with goals. Assess the environmental impacts of different ideas and concepts. Use preliminary LCA to compare the potential environmental performance of various options and select those with the least negative impact.

B.1.3.1 Research, Prototyping, Testing and Feedback

This stage involves the creation of prototypes or models to test and validate concepts. Collect feedback from stakeholders, users, or testing environments to refine and improve the design.

Conduct LCA for prototypes to evaluate their environmental impact. Use the results to refine and optimize the design, addressing issues like resource use, emissions, and waste before finalizing the product.

B.1.3.2 Product, System or Service Definition

This stage involves finalizing and documenting the detailed specifications and features of the product, system, or service. This step involves defining functionality, performance criteria, and design requirements to guide the subsequent stages.

Define environmental criteria and performance targets for the product or service. Include sustainability goals in the product specifications, such as reduced carbon footprint, lower energy consumption, or use of recycled materials.

B.2 Upstream Stage

B.2.1 Material / Resources Extraction and Refining

This stage involves extracting raw materials from natural sources or suppliers. Process these materials to remove impurities and prepare them for use in manufacturing. This step ensures the materials meet the necessary quality and safety standards.

Assess the environmental impact of material extraction and refining processes. Select materials that have lower environmental impacts, such as those with lower energy requirements or those that are sustainably sourced.

B.2.2 Material / Resources Processing and Forming

This stage involves transforming raw materials into usable forms through various processing techniques. This may include shaping, molding, or altering materials to meet specific requirements for production.

Evaluate the environmental impact of material processing and forming. Optimize processes to reduce energy use, emissions, and waste. Implement recycling or reprocessing where possible.

B.2.3 Part / Components Production

This stage involves manufacturing individual parts and components that will be assembled into the final product. This step involves precision engineering and quality control to ensure each part meets the required specifications.

Perform LCA on the production of parts and components to identify areas where environmental impacts can be reduced. Focus on energy efficiency, resource conservation, and waste reduction during manufacturing.

B.2.4 Sub-assembly Manufacturing Process

This stage involves combining individual parts and components into sub-assemblies, which are intermediate products that will eventually be integrated into the final product. This process may involve multiple steps and techniques to ensure proper function and quality.

Analyze the environmental impacts of sub-assembly processes. Optimize assembly techniques to minimize energy use and material waste. Evaluate opportunities for using eco-friendly materials and improving efficiency.

B.3 Core Stage

B.3.1 Product Assembly and Testing

This stage involves assembling sub-assemblies and individual components into the final product. Perform rigorous testing to ensure the product meets all design specifications, quality standards, and regulatory requirements.

Assess the environmental impact of the final product assembly and testing phases. Aim to reduce resource use and emissions during assembly. Ensure testing processes are efficient and environmentally friendly.

B.3.2 Product Marketing, Sales, Customer Request and Support

This stage involves developing and implementing marketing strategies to promote the product. Handle sales transactions, respond to customer inquiries, and provide ongoing support to ensure customer satisfaction and address any issues.

Consider the environmental impacts of marketing and sales activities. Use eco-friendly materials for packaging and promotional materials. Provide information on the product’s environmental benefits to customers and support sustainable practices.

B.4 Use, operation and maintenance stages

B.4.1 Product use or operation, materials or resources use, spare-parts use and maintenance

This stage involves facilitating the use of the product by consumers, manage the consumption of materials or resources, provide spare parts as needed, and perform regular maintenance to ensure the product remains functional and efficient.

Evaluate the environmental impact of the product’s use phase. Focus on energy efficiency and resource conservation during the product's operational life. Offer services that promote maintenance and repair to extend the product’s lifespan and reduce waste.

B.5 End-of-life stage

B.5.1 Product / Sub-assembly / Component / Material End-of-Cycle

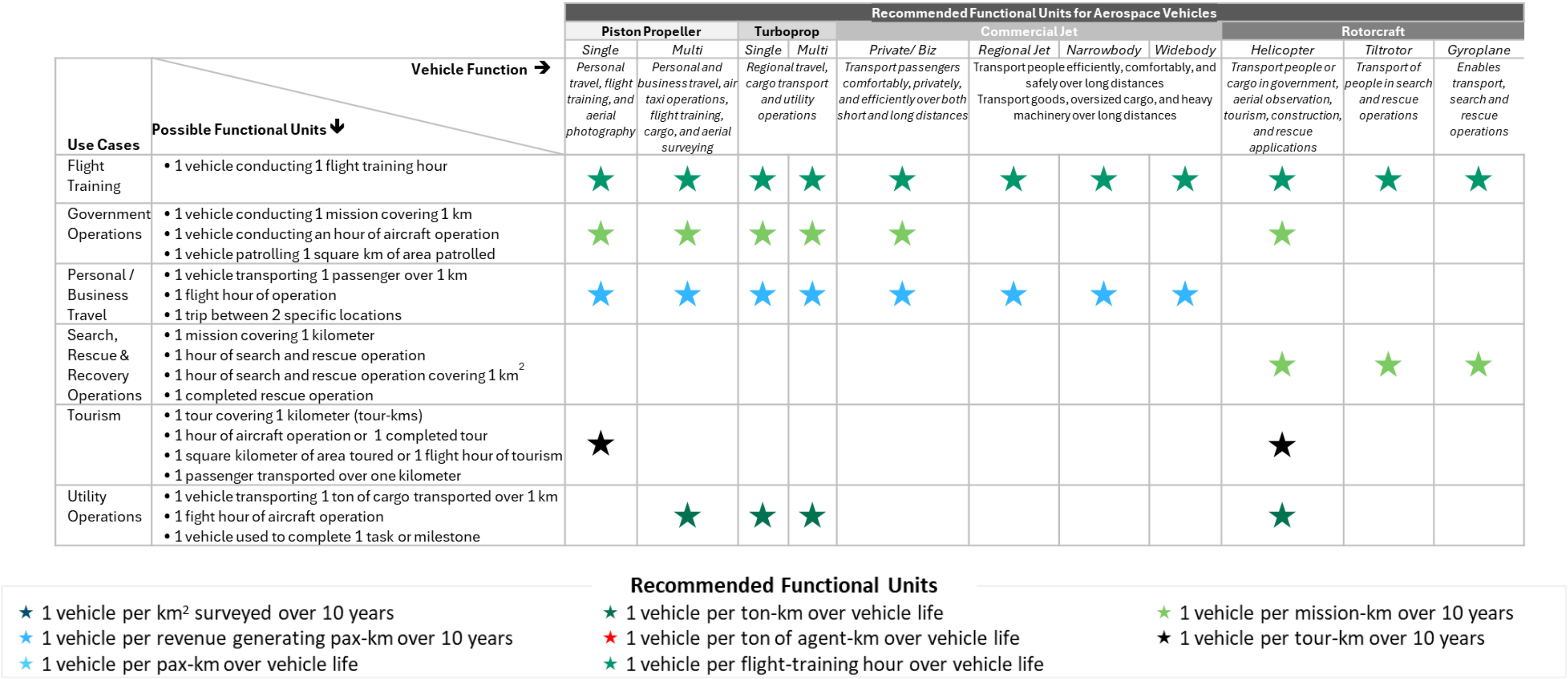
This stage involves managing the end-of-life phase for the product, sub-assemblies, components, or materials. This may involve recycling, disposal, or repurposing, with the goal of minimizing environmental impact and recovering valuable resources.

Perform a final LCA to assess the end-of-life impacts of the product, sub-assemblies, components, or materials. Implement strategies for recycling, reuse, or safe disposal to minimize environmental impact. Develop plans for recovering valuable materials and reducing landfill waste.

Appendix C: Functional Unit examples across aerospace products - commercial and defense vehicles

Defined in the table below is the Functional Unit Decision Matrix for commercial aerospace vehicles.

The columns represent the various commercial aerospace vehicle functions, and the rows of the matrix propose possible functional units (FU). The noted stars represent some of the recommended FU for each vehicle type. Please note the table is not exhaustive. Other Functional Units can be used, notably the Functional Unit used for Business Jets in their Product Category Rule is to: “transport 1 cubic meter of accommodation space for leisure of business purposes over 100km for a given typical mission length”[10].



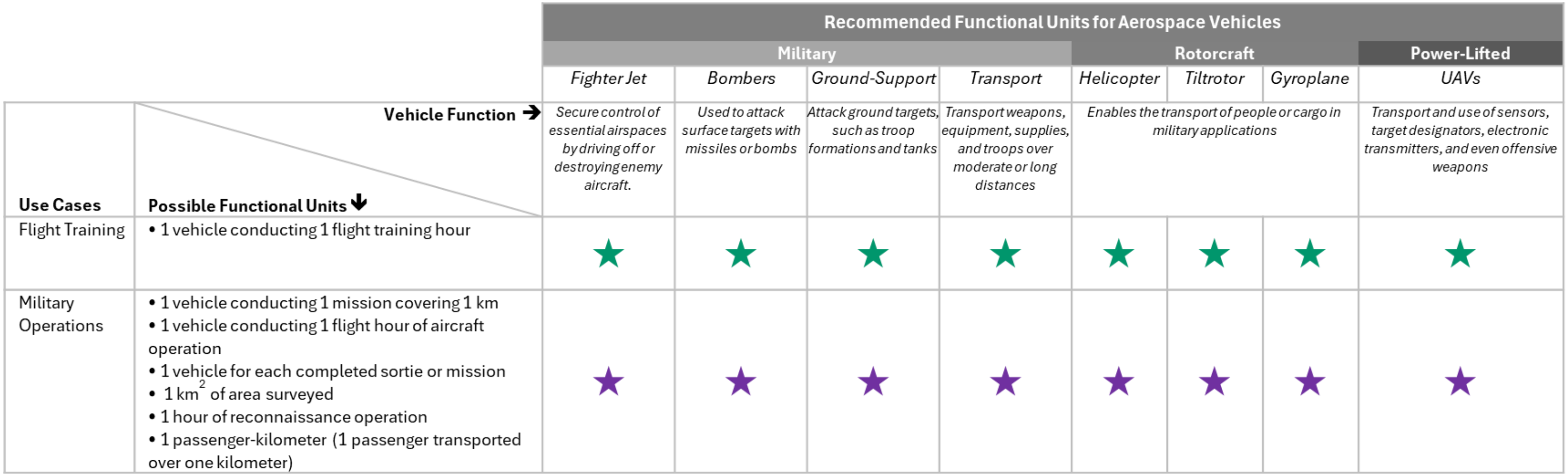
		Recommended Functional Units for Aerospace Vehicles										
		Piston Propeller		**Turboprop**		**Commercial Jet**				**Rotorcraft**		
		Single	*Multi*	*Single*	*Multi*	*Private/ Biz*	*Regional Jet*	*Narrowbody*	*Widebody*	*Helicopter*	*Tiltrotor*	*Gyroplane*
Use Cases	**Vehicle Function →** **Possible Functional Units ↓**	*Personal travel, flight training, and aerial photography*	*Personal and business travel, air taxi operations, flight training, cargo, and aerial surveying*	*Regional travel, cargo transport and utility operations*		*Transport passengers comfortably, privately, and efficiently over both short and long distances*	Transport people efficiently, comfortably, and safely over long distances Transport goods, oversized cargo, and heavy machinery over long distances			*Transport people or cargo in government, aerial observation, tourism, construction, and rescue applications*	*Transport of people in search and rescue operations*	*Enables transport, search and rescue operations*
Flight Training	• 1 vehicle conducting 1 flight training hour	★	★	★	★	★	★	★	★	★	★	★
Government Operations	• 1 vehicle conducting 1 mission covering 1 km • 1 vehicle conducting an hour of aircraft operation • 1 vehicle patrolling 1 square km of area patrolled	★	★	★	★	★				★		
Personal / Business Travel	• 1 vehicle transporting 1 passenger over 1 km • 1 flight hour of operation • 1 trip between 2 specific locations	★	★	★	★	★	★	★	★			
Search, Rescue & Recovery Operations	• 1 mission covering 1 kilometer • 1 hour of search and rescue operation • 1 hour of search and rescue operation covering 1 km^2 • 1 completed rescue operation									★	★	★
Tourism	• 1 tour covering 1 kilometer (tour-kms) • 1 hour of aircraft operation or 1 completed tour • 1 square kilometer of area toured or 1 flight hour of tourism • 1 passenger transported over one kilometer	★								★		
Utility Operations	• 1 vehicle transporting 1 ton of cargo transported over 1 km • 1 fight hour of aircraft operation • 1 vehicle used to complete 1 task or milestone		★	★	★					★		

Recommended Functional Units

- ★ 1 vehicle per km^2 surveyed over 10 years
- ★ 1 vehicle per revenue generating pax-km over 10 years
- ★ 1 vehicle per pax-km over vehicle life
- ★ 1 vehicle per ton-km over vehicle life
- ★ 1 vehicle per ton of agent-km over vehicle life
- ★ 1 vehicle per flight-training hour over vehicle life
- ★ 1 vehicle per mission-km over 10 years
- ★ 1 vehicle per tour-km over 10 years

Functional Unit Decision Matrix for defense-based aerospace vehicles

Defined in the table below is the Functional Unit Decision Matrix for defense-based aerospace vehicles. The columns represent the various commercial aerospace vehicle functions, and the rows of the matrix propose possible functional units (FU). The noted stars represent the recommended FU for each vehicle type.



		Recommended Functional Units for Aerospace Vehicles							
		Military				**Rotorcraft**			**Power-Lifted**
		Fighter Jet	*Bombers*	*Ground-Support*	*Transport*	*Helicopter*	*Tiltrotor*	*Gyroplane*	*UAVs*
Use Cases	**Vehicle Function** ➔ **Possible Functional Units** 🡻	*Secure control of essential airspaces by driving off or destroying enemy aircraft.*	*Used to attack surface targets with missiles or bombs*	*Attack ground targets, such as troop formations and tanks*	*Transport weapons, equipment, supplies, and troops over moderate or long distances*	*Enables the transport of people or cargo in military applications*			*Transport and use of sensors, target designators, electronic transmitters, and even offensive weapons*
Flight Training	• 1 vehicle conducting 1 flight training hour	★	★	★	★	★	★	★	★
Military Operations	• 1 vehicle conducting 1 mission covering 1 km • 1 vehicle conducting 1 flight hour of aircraft operation • 1 vehicle for each completed sortie or mission • 1 km^2 of area surveyed • 1 hour of reconnaissance operation • 1 passenger-kilometer (1 passenger transported over one kilometer)	★	★	★	★	★	★	★	★

Recommended Functional Units

★ 1 vehicle per flight-training hour over vehicle life
★ 1 vehicle per completed mission over vehicle life