INTERNATIONAL AEROSPACE ENVIRONMENTAL GROUP

Aerospace Life Cycle Assessment (LCA)

Framework for improved connectivity

December 2025

*Version **02***

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

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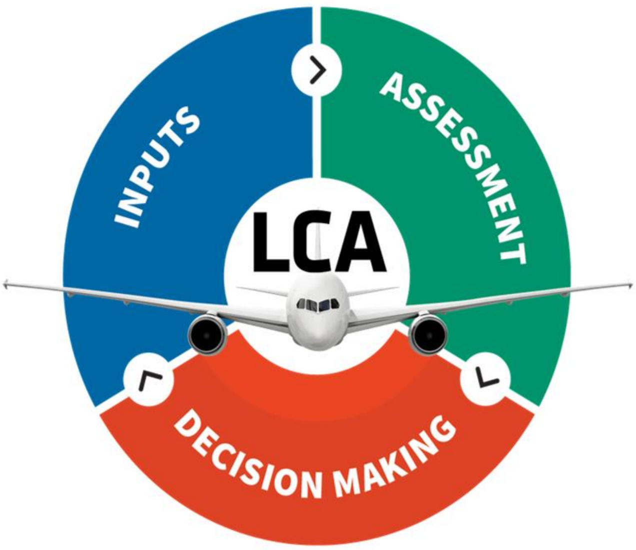

Version History

Date	v#	Modified By	Section, Page(s) and Text Revised
22 April 2025	1	Garcia Garriga, A.	First released version
November 12th 2025	2	Garcia Garriga, A.	Section 1,3,5,6, Appendix A

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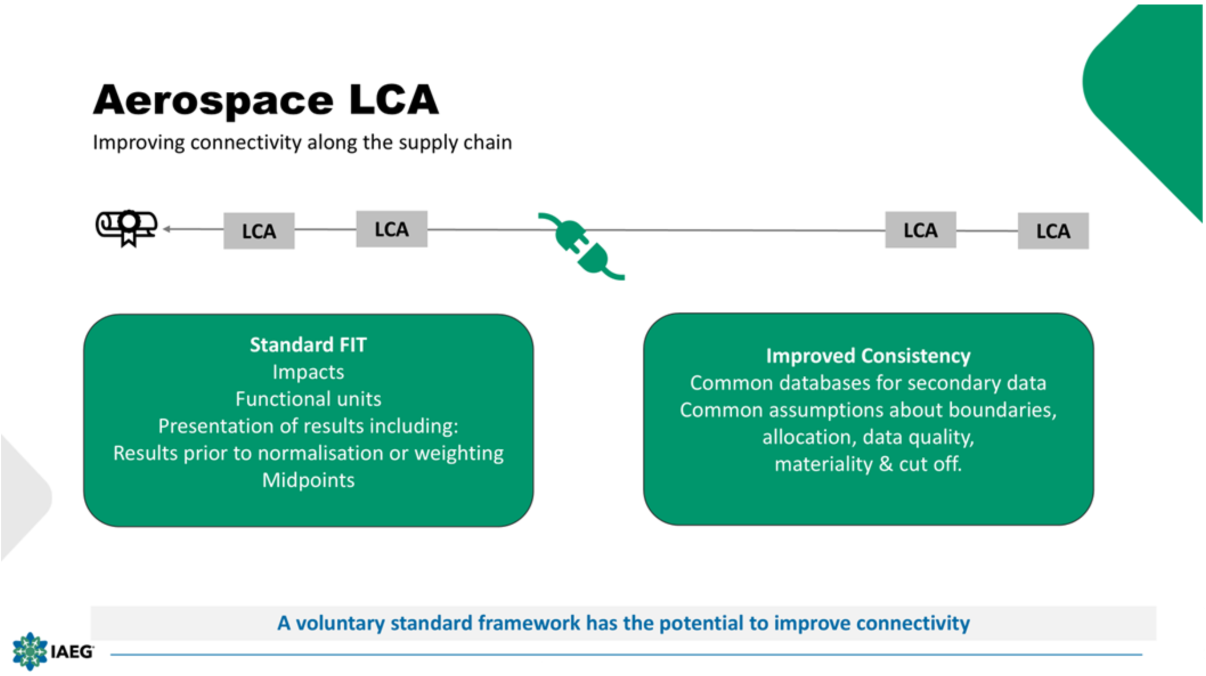
EXECUTIVE SUMMARY

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. Initial versions of this standard framework are 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 ensuing versions of this standard framework.



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 Gases

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

PCF – Product Carbon 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. LCA is a multicriteria approach that goes beyond climate change and considers other environmental impacts. 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. Typical lifecycle of an aerospace product

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

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 natural resources depletion. 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] and ISO:14044[2] 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, ISO:14044 and other recognized standards in LCA to the aerospace industry to reduce the variability in data harvesting and calculation method across aerospace companies.

Table 1 below lists of some of the relevant standards for Lifecycle assessment, carbon footprinting and ecodesign in general that might be cited within this document and that serve to frame the approach specifically for aerospace companies and products

Table 1. List of relevant standards on LCA and environmental emissions

Standard/ Guideline	Scope	Main Focus	Application Level	Notes
ISO 14040 / 14044	Product	Principles and requirements for LCA	International	Foundation for other LCA standards
ISO 14067	Product	Carbon footprint of products	International	Excludes carbon offsetting
ISO 14020–14026	Product	Environmental labeling	International	Communication of environmental information
ISO 14063	Organization	Environmental communication	International	Internal and external communication
ISO 14064 (1,2,3)	Organization /Project	GHG and removals	International	Quantification and verification
ISO 14080	Organization	GHG management and climate actions	International	Mitigation and adaptation
ISO 14069	Organization	Application of ISO 14064-1	International	Direct and indirect emissions
ISO 14072	Organization	Application of LCA to organizations	International	System boundary considerations
ISO 14001–14009	Organization	Environmental management	International	Includes ecodesign and monetary evaluation
GHG Protocol	Product/ Organization	GHG emissions	Global	Scopes 1, 2, and 3
PEF/OEF (EU)	Product/ Organization	Environmental footprint	Europe	Category/sector-specific rules
ISO 14068 (in development)	Organization	Carbon neutrality	International	Part of ISO 14060 family
ISO 14074 (in development)	Product	LCA normalization and interpretation	International	Complements ISO 14040/44
ISO 14097 (in development)	Organization	GHG reporting in finance	International	Focus on climate-related investments

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. More details on the possible use cases for LCA are included on Section 2 of this document.

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. This document does not aim to reconcile the product-based approach (LCA) and the corporate-based approach (Scopes 1, 2 and 3) to greenhouse gas emissions accounting. Guidance on the latter exists as part of IAEG WG3.

Lifecycle Assessment is part of a wider effort to reduce the environmental impact of aerospace products and ensure 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 assessments, recipients of lifecycle 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**[3]. This standard emphasizes the need for **Product Category Rules (PCRs)** to produce EPDs for external release.

Another important external declaration that is the result of an LCA is the release of **a Product Carbon Footprint (PCF)**. Different upcoming regulations put an emphasis on capturing the carbon footprint at product level (different from corporate GHG emissions accounting). A product carbon footprint study is a single criteria LCA study, if the intention is to release it externally it should follow the standards of external LCA use cases.

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 use).
- **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[4] , Eco-design for sustainable product regulation (ESPR)[5], 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 and avoid burden shifting across product life cycle phases or impacts.

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 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 approach

Based on the terms and concepts proposed in the ILCD Handbook[11], two main types of LCA approaches are distinguished: **attributional** and **consequential.** The choice between each approach guides other methodological decisions in the LCA, such as the choice of input data and the modeling of processes with multiple products.

Attributional LCA aims to estimate the share of global environmental burdens that can be attributed to the studied system or to **describe the environmentally relevant physical flows to and from a life cycle and its subsystems**. This modeling principle is often referred to as “accounting,” “book-keeping,” “retrospective,” or “descriptive.”

<u>Example</u>: For SAF, an attributional LCA would calculate the GHG emissions associated with the production and use of one liter of SAF, based on the current production processes, without considering potential changes in market dynamics or stakeholder behaviors.

Consequential LCA seeks to estimate how the production and use of the studied system affect global environmental burdens or to **describe how environmentally relevant flows will change in response to possible decisions**. This approach is based on modeling principles sometimes called “change-oriented,” “effect-oriented,” “decision-based,” or “market-based.” It evaluates the environmental consequences of a decision or a marginal change in the system, taking into account indirect effects and market responses.

<u>Example</u>: For SAF, a consequential LCA would assess the overall environmental impact of increasing the demand for SAF, considering effects such as changes in agricultural practices, shifts in land use, or impacts on global fuel and agricultural markets.

In this framework, the term LCA refers only to attributional LCA.

3.2 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:

- Study goals (Section 0)
- Intended application of the study (Section 3.2.2)
- Target audience (Section 3.2.3)
- Commissioner (customer) of the study and other influential actors (Section 3.2.4)
- Limitations of method, assumptions, data etc. (Section 3.2.5)

3.2.1 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:

- Assessing the potential environmental impacts of an individual product (good or service) and the relative contributions of different materials and processes
- Supporting the development of environmentally optimal products by modelling various scenarios and establishing design requirements for environmental sustainability
- Releasing claims about the environmental impact of your product externally whether comparing it to a previous product or a competitor's 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.

3.2.2 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:

- Compare the environmental impacts of different products systems with the same functions
- Identify hotspots where the most significant environmental impact occurs over the lifecycle of a product system
- Evaluate improvement of design and process choices during decision making
- Report on environmental impacts, responding to policy and legislative requirements
- Produce an eco-label
- Produce a Product Carbon Footprint (PCF)
- Produce an EPD based on a PCR
- Support policy development which considers environmental impacts

3.2.3 Target Audience

The target audience should be identified and reported on. In most cases, this will include the study commissioner and all key stakeholders, including reviewers as needed. 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. For example, any comparative LCA intended for public disclosure requires a critical review according to the ISO standard, the topic of critical reviews is covered in Section 6 of this document.

3.2.4 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.

3.2.5 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.

3.3 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 3.3.1)
- Functional unit (Section 3.3.2)
- Reference flows (Section 3.3.3)
- System boundaries (Section 3.3.4)
- Exclusion criteria (Section 3.3.5)
- Modelling approaches (Section 3.3.6)

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.

3.3.1 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. The functions can be determined based on a functional analysis. Some aerospace examples of functions are included in the table below (

Table 2) and illustrated in Figure 2.

Table 2. Example of 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 paint	To cover aircraft surfaces with a given degree of opacity	Protects the aircraft surface from weathering and UV effects and adds brand recognition to operators
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
Satellite	To transport a payload in orbit around a celestial body	Combines various subsystems including power unit, telemetry and instrumentation to achieve orbit around a celestial body for a given amount of time
Satellite instrumentation	To observe, measure, quantify, phenomena in orbit	Measuring or observation equipment designed to gather data from orbit
Launch vehicle	To transport a payload into space	Moves satellites and other space vehicles from earth to orbit or outer space
Training simulator	To train crew on necessary operations for mission success	Replicates existing systems physically or virtually on ground
Air-traffic management ground system	To manage and control the air traffic in a given region to avoid accidents and mitigate risk	Air traffic management systems include many subsystems and data streams such as surveillance, communications, weather information etc.

Figure 2. Examples of functions

3.3.2 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 3. Examples of functional units 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 paint	To cover aircraft surfaces with a given degree of opacity	Provide protection of 1 m^2 area substrate for 30 years with a minimum 95% opacity.
Aircraft	To transport people and/or cargo	Transport a passenger/a kg of payload 10,000 nautical miles
Satellite	To transport a payload in orbit around a celestial body	Transport 10 kg of a given payload in orbit for 10 years
Satellite instrumentation	To observe, measure, quantify, phenomena in orbit	Observe weather patterns for 10 years with a given degree of accuracy
Launch vehicle	To transport a payload into space	Carry a payload of 500kg into Low Earth orbit
Training simulator	To train crew on necessary operations for mission success	Train a crew member onsite and o the ground to a satisfactory level in 100hrs
Air-traffic management ground system	To manage and control the air traffic in a given region to avoid accidents and mitigate risk	Detect and manage all flights in an area of 50km2 for 50 years.

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.”

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 paint 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.

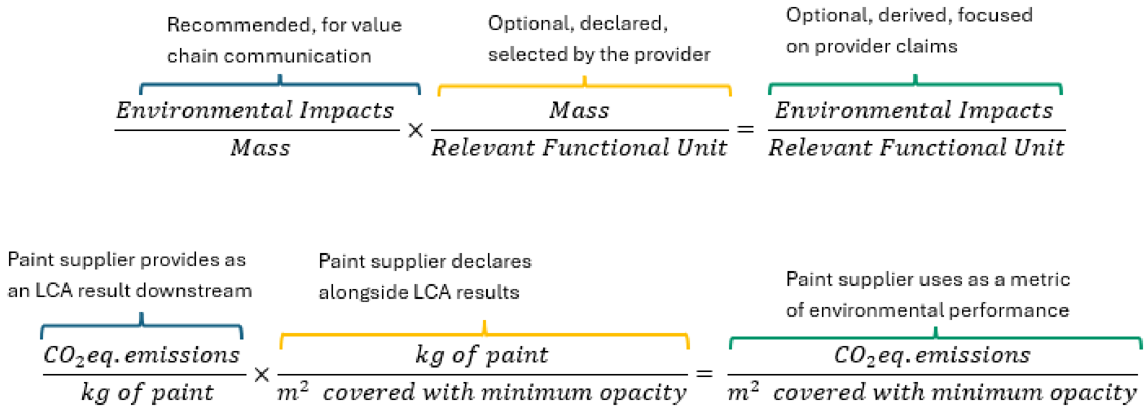


Figure 4. Examples of declared and recommended Functional Units

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.

3.3.3 Reference Flows

Based on ISO 14040, the reference flow is: "measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit"[1]. 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 according 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

Thes input/output flows for the chosen reference flow 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 4. Example of reference flow and functional unit relationship

System:	**Aircraft**	
Function:	To transport people	
Functional unit (FU):	*To transport 135 passengers 1500 nmi*	
Reference flows:	Aircraft 1 (narrow body) — capacity 135 passengers	Aircraft 2 (widebody) — capacity 525 passengers
Performance:	Aircraft 1 — 5,300 litres of fuel consumption per 1,500 nautical miles	Aircraft 2 — 15,000 litres of fuel consumption per 1,500 nautical miles
Scaling factor (Calculation required to fulfill the functional unit:):	Aircraft 1 — 135/135	Aircraft 2 — 135/525
Input flow for fuel allocation:	Amount of fuel required to fulfill the functional unit: Aircraft 1 — 5300 litres per FU	Amount of fuel required to fulfill the functional unit: Aircraft 2— 3857 litres per FU

3.3.4 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. An analysis which comprises upstream activities, the companies own operations and also includes downstream activities reaching the products end-of-life is called cradle-to-grave. Cradle-to-grave analysis is the most complete analysis as it provides a more complete understanding of a products environmental impact throughout its lifecycle but it requires significant LCA expertise and a significant effort in gathering data along the value chain actors.

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.

For some intermediate products, where their design can be applied to multiple end uses, and the provider has limited visibility on the downstream processes, a cradle-to-gate assessment might be appropriate. For example, an LCA on a steel bolt.

However, a cradle-to-grave analysis in a complex value chain requires a set of common assumptions for the use and disposal phase and a clear agreement on boundaries and assumptions upfront. Use of common reference data for some of the critical processes precludes the use of primary data per operator but ensures consistency across the supply chain. For a more detailed discussion on some of these challenges this see section 3.3.6.1.

A summary of the system boundary options depending on the use case and goal is outlined in Table 5 below and can serve as quick reference. A visual guide to the different boundaries can be found in *Figure 6* and Figure 7.

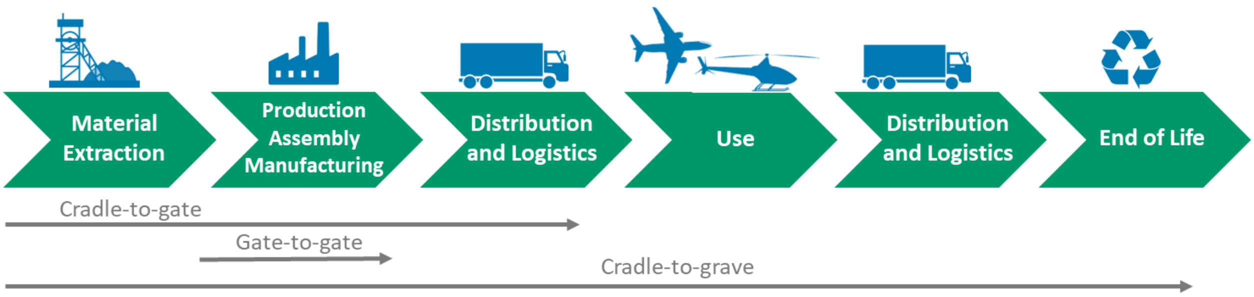


Figure 6. Illustration of system boundaries

Table 5. 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	Covers only the operations of the reporting company. Generally focuses on a specific operational step or process	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	Use to isolate operational impacts (e.g., fuel consumption, maintenance) and end-of-life

	from when the product is delivered to the customer	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 5.

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).

If necessary, exclusion of specific upstream and downstream activities should be clearly and transparently reported. Note that these exclusions should meet the cut off criteria outlined in section 3.2.5.

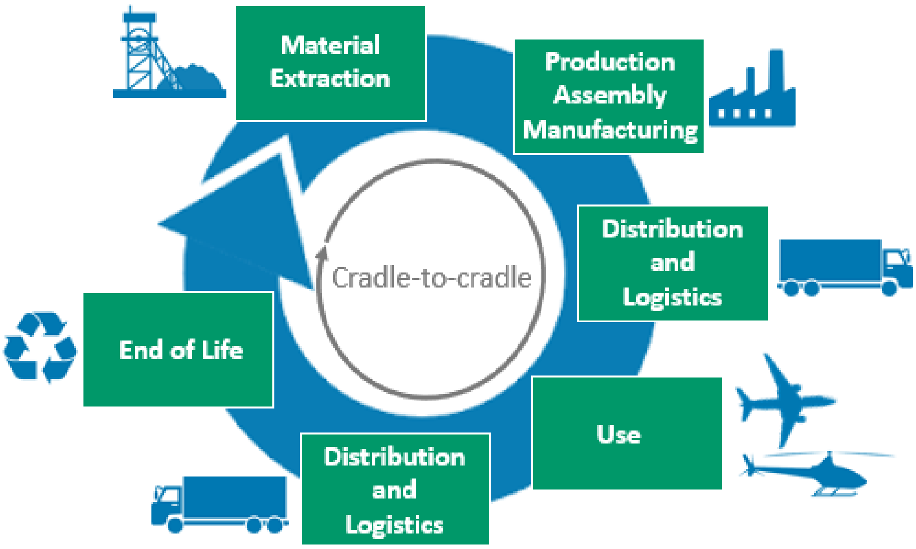


Figure 7. Cradle-to-cradle system boundary for a circular product lifecycle

3.3.5 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 and the results will remain compliant with any relevant regulation if declaring the results externally.

Commonly, the default cut-off rules are:

- Mass: if a flow is less than 1% of the mass at either a product-level or individual-process level, then it may be excluded, provided its environmental relevance is immaterial except for specific substances of concerns such as those subject to specific regulations like REACH, RoHS.

- Energy: if a flow is less than 1% of the energy at either a product-level or individual-process level, then it may be excluded, provided its environmental relevance is immaterial,

- The total of neglected input flows per stage (within scope) may be a maximum of 5% of energy usage and mass. 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 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

It is not always obvious before performing the study whether a process can be cut off as its contribution to the total LCA results for the product system are not yet known. Below are some approaches that can be used by the practitioner to help with identifying which processes can be cut-off:

- **Iterative LCA:** All processes to be included in the LCI model at first, using LCA iteratively to identify if they are significant or not. A sensitivity analysis should be completed at the end of the study to justify any cut-off using this approach.
- **Mass-based cut-off criteria:** If a process delivering less than 0.1% of the reference flow can be cut-off. However when using this approach please be aware that even if a flow is quantitatively small in mass share, it still may contribute significantly to the total impact. An example is gold in electronics, which by mass is small, however due to mining activities can mean its impacts are significant. User experience and expert judgement are required.
- **Qualitative justification:** The LCA practitioner can use their experience and knowledge to argue what processes can be cut-off. For example, if a practitioner has completed similar studies in the past and knows that particular stages or processes are negligible in impact, they can provide justification for exclusion.
- **Confidentiality-Based Cut-Off:** When data is proprietary or sensitive, it may be excluded or replaced with generic data, provided it does not significantly affect the results and that this exclusion and justification is agreed on by all parties involved in the LCA study.

For all approaches, the practitioner must document, report and justify any cut-off decisions.

3.3.6 Modelling Approaches

In order to perform an LCA, a model of the product should be developed once the LCA scope and functional unit is decided. The 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.

In Life Cycle Assessment (LCA) studies within the aerospace industry, safeguarding sensitive data is critical due to the proprietary nature of materials, internal processes, and supply chains. To ensure confidentiality, practitioners should employ techniques such as anonymizing data sources, which involve removing or masking identifiers that could trace information back to specific suppliers, technologies or materials. Aggregating data across multiple entities or product lines can further obscure individual contributions while preserving analytical value. Additionally, establishing Non-Disclosure Agreements (NDAs) with data providers ensures legal protection and trust, enabling more transparent collaboration. These measures, among others, combined with secure data storage and controlled access protocols, help maintain compliance with industry standards and protect intellectual property throughout the LCA process for the aerospace industry.

3.3.6.1 Approach to LCA along the value chain

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 an LCA it is important to define the system boundary for each actor and define which value chain actor will model what and what LCI data will be provided by each participant.

An upfront agreement on the boundaries and responsibility over modelling of each analysis is needed and an inclusion of system boundary flow diagram with the different actors, their responsibilities and the interfaces agreed between them helps clarify the flow of information across organizational boundaries. WG12 intends to continue working to provide useful template documents to clarify these roles and helps gather data and results in a more standardized manner.

This is particularly relevant for some examples of LCA products where the scope of the LCA and its communication along the value chain could jeopardize methodology compatibility. For example, on biogenic carbon accounting, the use of -1/+1 approach that considers CO2 uptake by biomass during growth (at -1) and its release at the end of life (at +1) could be misinterpreted when looking only at the cradle-to-gate scope and only including the growth aspect. Thus, this -1/+1 method mandates a consistent cradle-to-grave approach throughout the analysis to reflect temporary carbon storage and end of life release to avoid overestimate benefits.

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 should be defined upfront. 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.

3.3.6.2 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[14] 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[14] 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[13].

3.3.6.3 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 metallic waste streams global average recycling rate ranges. 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.

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.

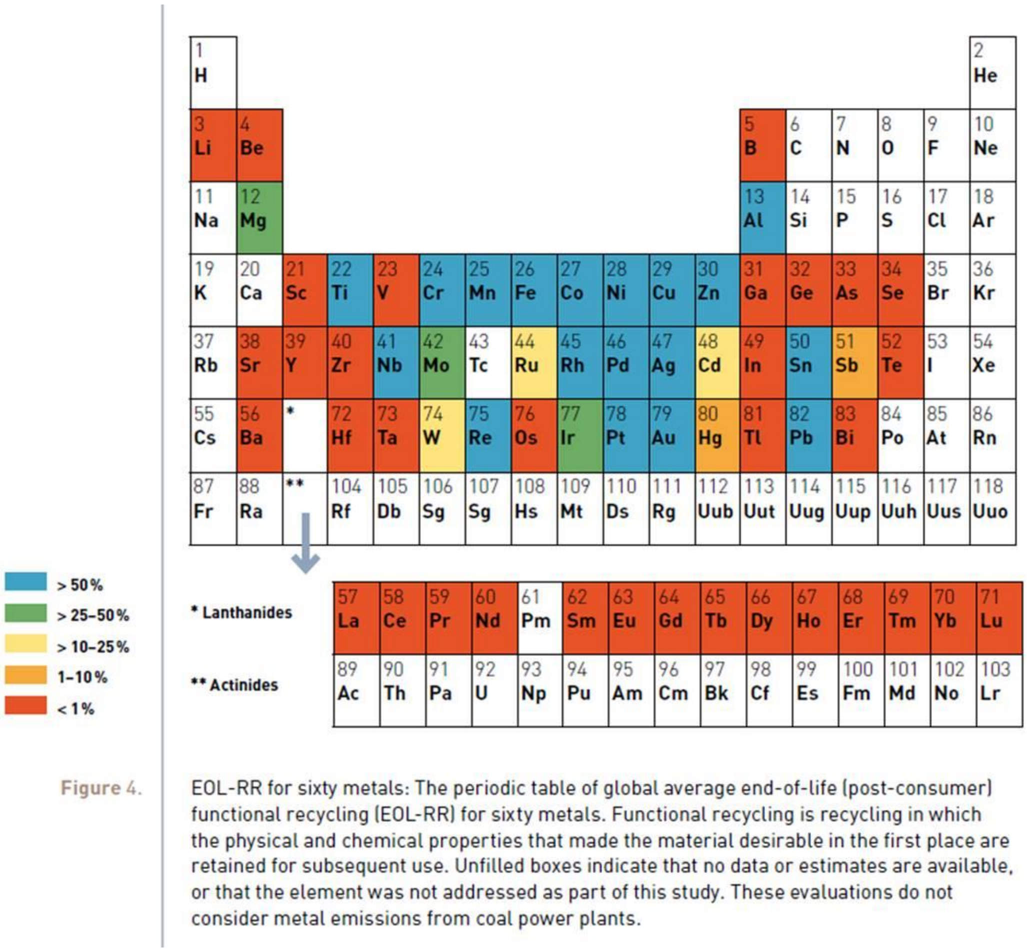


Figure 8. Illustration of global average recycling rate ranges for some metals[18]

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. .

Should recycled material be used alongside with primary material in the production of a component the burden – impact of primary production and impact of processing of recycled materials - will be accounted based on the real mass share of recycled and primary material.

- 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[19] 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[19], 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.

3.4 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.

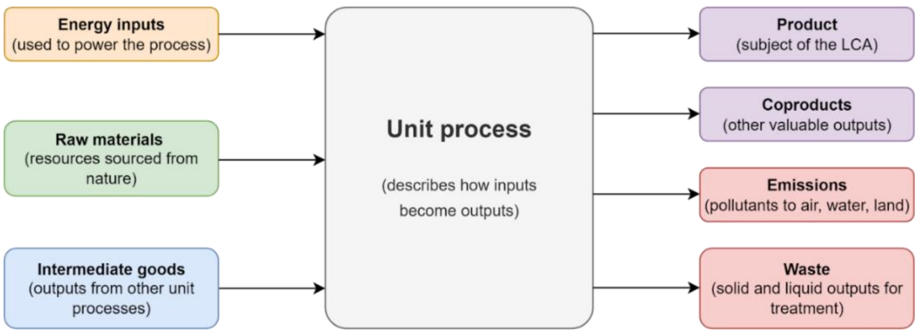


Figure 9. Structure of a unit process used in LCA studies, with physical and energy input flows and product and pollutant output flows. Credit: Yordas

3.4.1 Data Types from their source origin

Data involved in an LCA can be typically categorized into two types based on the source of the data: primary data and secondary data.

Primary (or company specific, or foreground) Data

- **Definition & Scope:** Primary data are **specific, study-relevant inputs** that describe processes directly under the control of the LCA practitioner or organization. These data are collected or measured explicitly for the system under study.
- **Characteristics**:
  - High specificity to the system's context (e.g., aircraft type, operational profile, materials).
  - Essential for capturing the unique performance and environmental behaviors of the focal system.
  - Highest burden to collect, measure and prepare
  - Often includes operational metrics, material specifics, and use-phase data.
- **Typical Examples for Aerospace LCA:**
  - Material composition of aerospace components (e.g., aluminum alloys, composites, fasteners).
  - Energy use during manufacturing, assembly, and testing.
  - Fuel or electricity consumption during operation.

Secondary (or background) Data

- **Definition & Role:** Secondary data are **generic datasets** representing upstream or peripheral processes not specific to the studied system. These fill in the gaps for parts of the supply chain or lifecycle stages not explicitly measured. Where secondary data is used in an LCA study it should be documented and the source referenced for transparency

- **Characteristics:**
  - Sourced from literature, scientific paper or established reference LCA databases
  - Provide context and completeness to the life cycle model, especially for upstream processes like material extraction or energy production.
  - Typically, they have lower precision relative to foreground data, yet critical for completeness.
- **Typical Examples for Aerospace LCA:**
  - Electricity grid mixes for different regions.
  - Emissions from raw material extraction and processing.

Why the Distinction Matters

- **Transparency & Traceability:** Clearly distinguishing these two types helps stakeholders understand what data is proprietary or context-sensitive (primary) versus what comes from broader, publicly available sources (secondary).

- **Data Quality Assessment:** Primary (Company Specific) data typically have high quality and relevance but may have gaps. Secondary/Reference data may be older or regionally generalized, or not clear in the aggregation requiring careful assessment for consistency.

- **Iterative Refinement:** According to ISO:14040/44, LCA practitioners may iteratively refine which data are primary or secondary as the goal and scope evolve.

- **Efficiency & Focus:** Collecting primary data is resource-intensive. Secondary data allows the model to remain comprehensive without excessive data collection.

Section 3.4.2 covers in a bit more detail some guidelines when collecting company specific data.

Table 6 below offers an overview of some of the data commonly found across aerospace LCAs and some example data sources to illustrate the varied nature and origin of the data used in LCAs

Table 6. 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*

3.4.2 Primary data collection guidance

Primary Data is directly measured or collected at a specific facility or set of facilities and is representative of one or more of the activities or processes in the system boundaries. All the known inputs and outputs for the process must be included. All of this data is generally gathered in a data inventory template. See IAEG WG12 website for a proposed template for data gathering.

The typical sources of primary data to collect to fill out the template are:

- process- or plant-level consumption data;
- bills and stock/inventory changes of consumables;
- emission measurements (amounts and concentrations of emissions from flue gas and wastewater);
- composition of products and waste;
- procurement and sale department(s)/unit(s)

It is recommended that company-specific data collection be done on an annual basis and be provided as a yearly average.

In a typical data gathering template the bill of material (BoM) has two parts: the list of materials/ingredients and the quantity used for each of them.

The activity data of the BoM should be specific to the product in scope and modelled with company-specific data. For companies producing more than one product, the activity data used (including the BoM) should be specific to the product covered by the study.

The modelling of the manufacturing processes should be based on company-specific data (e.g. energy needed to assemble the materials/components of the product in scope). For companies producing more than one product, the activity data used should be specific to the product covered by the study either through direct measurement and collection or through system expansion and allocation as covered in section 3.4.6, and any and all allocation methods declared as part of the analysis,

The company-specific data to be collected for the creation of company-specific datasets should include all known inputs and outputs for the processes concerned, including:

As inputs:

- material inputs that end up in the product, including minerals and metals, semi-finished materials and chemical feedstocks;

- energy that is consumed directly and indirectly in the processing plant, such as electricity, steam, thermal energy required by the process;
- auxiliaries and any other material inputs required for the manufacturing process, such as chemicals, cleaning material, lubricants, and refrigerants;
- transport distances and means of transport within the predefined boundary of company-specific data

As outputs:

- any material output, including wastewater;
- any elementary flow; Emissions that are not accounted for in the corresponding energy process dataset and that are not monitored via measurements shall be estimated.

Company-specific emission data may be based on direct measurements or be calculated by combining it with reputable reference data, scaling it, aggregating it or allocating it in order to match the predefined study boundaries and reference flow of the study. All data sources and mathematical treatments applied to the data shall be provided and explained in the carbon footprint study report.

3.4.3 Types of secondary data

When considering secondary data from literature or aerospace databases it is important to consider not only the existence of a particular dataset (is there a line item for a particular material or process) but also the origins and scope of it. In some cases a particular dataset might be representative of a process from a specific region or include aggregated data from multiple regions or processes this means that an LCA practitioner should be aware of the type of secondary data they are selecting from a geographical standpoint but also consider whether it is aggregated data or not.

A summary of these considerations is included in Figure 10below

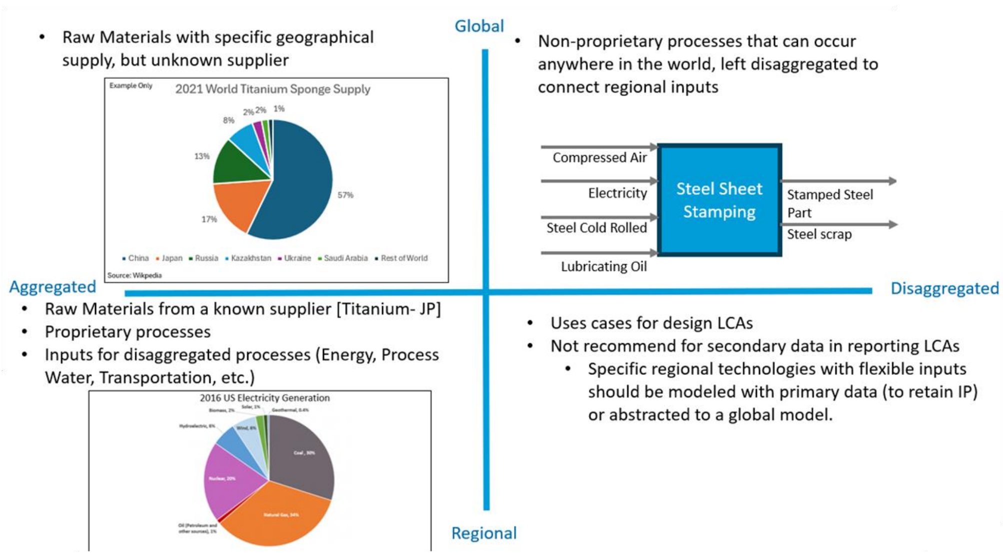


Figure 10. Types of secondary data: aggregated vs. disaggregated, global vs. regional

3.4.4 Secondary or reference data gaps

Addressing data gaps with aerospace specific data in current 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.
- **ESA LCA database**: Focused on space systems and developed by the European Space agency. Works only within EU countries and with an existing EcoInvent license

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.

3.4.5 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.

3.4.5.1 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.

This framework document recommends the use of global average impact factors for fuel-related secondary data, not regionally specific ones unless for very specific study goals. 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.

In general, this document also recommends assuming 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.

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.

Dealing with SAF:

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.

3.4.5.2 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 and the presence of such contracts and changes to regional emissions factor should be properly documented and justified.

3.4.5.3 Transport

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.

3.4.6 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.

Mass-allocation example: Thermal batch process (Curing, Coating, Heat treatment)

Various components are treated simultaneously in a thermal process. Examples include curing CFRP components in a convection oven or autoclave, heat treatment, and coating of metal components. Since energy consumption and heating behavior depend, among other things, on the mass of the components, mass allocation of energy consumption and any other media that may be required, such as inert gases, is preferable to pure quantity allocation. Alternatively, the component volume can also be used, as it has a significant influence on the oven's loading.

Time-allocation: Machining processes such as milling

Cooling lubricants are frequently employed in machining processes. This can be supplied by central cooling lubricant pumps. Even when the machining processes are not productive, the cooling lubricant must be circulated. The energy consumption of the lubricant pumps during non-productive phases can be allocated to the manufactured components on a time-based allocation basis. This is achieved by calculating the ratio of the process time of the manufactured part to the total process time of all manufactured parts that receive lubricants from the central pump.

3.4.7 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 the study commissioner to determine.

- **Technological Representativeness** is the degree to which the data reflects 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 reflects 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.
- **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 for a simple approach are summarized in *Table 7*.

Table 7. 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, with a 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[11], Catena-X guideline[16], Ecoinvent[17], PEF[19], or the ESA[20] LCA handbook.

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, employing numerical data quality ratings (DQR) for uncertainty assessments as defined in certain methodologies 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.

3.4.7.1 Data Quality on Upstream processes

The data composing the final product collected from suppliers and sub-tiers, is compiled following a data collection process discussed in Section 3.4.2.

However, this data from multiple sources usually requires manual checks on consistency (units, parametrization, reference flow scaling). The initial data quality and data quality estimation is sometimes poor in an initial pass and some iterations across value chain partners are needed before it can be incorporated into the final LCA model. This can be improved through the use of standardized templates, through supplier specific guidance and training, by having dedicated LCA personnel to help with supplier and sub tier questions, and through practice. Subsequent LCAs carried out with the same partners are likely to present less consistency issues as the boundaries are better defined and teams become familiar with LCA methodology. 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.

3.5 Impact categories and calculations

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3.5.1 Integrating Lifecycle Impact Assessment (LCIA) Methods

This sub-section provides an overview of the most commonly used LCIA methods within the aerospace sector frameworks (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 unless otherwise specified by a PCR or product regulation. Final choice of method is a voluntary and unilateral decision of each company.

3.5.2 Midpoint Indicators for Detailed Assessment

In Life Cycle Impact Assessment (LCIA), results can be characterized using **midpoint** or **endpoint indicators** along the cause–effect chain. An example of this from the ReciPe method is included in

Midpoint Indicators: Midpoints represent environmental impacts at an **intermediate stage** between the inventory data (e.g., CO_2, NO_x, SO_x emissions) and the final damage to areas of protection. Examples include climate change potential, acidification potential, eutrophication potential, and resource use.

- **Advantages**:
  - Lower uncertainty (fewer modeling steps)
  - More detailed and process-specific
  - Well-documented and widely used in aerospace LCAs
- **Application**: Midpoint results allow practitioners to identify “hotspots” in the lifecycle and target improvements in specific materials, processes, or energy sources.

Endpoint Indicators : Endpoints represent the **final impacts** on areas of protection. For example, Human health (e.g., disability-adjusted life years lost), Ecosystem quality (e.g., biodiversity loss, species extinction), Resource availability (e.g., future extraction costs)

- **Advantages**: Easier to communicate to non-technical stakeholders (final outcomes).
- **Limitations**: Higher uncertainty due to complex cause–effect modeling and potential loss of detail in process-level contributions.

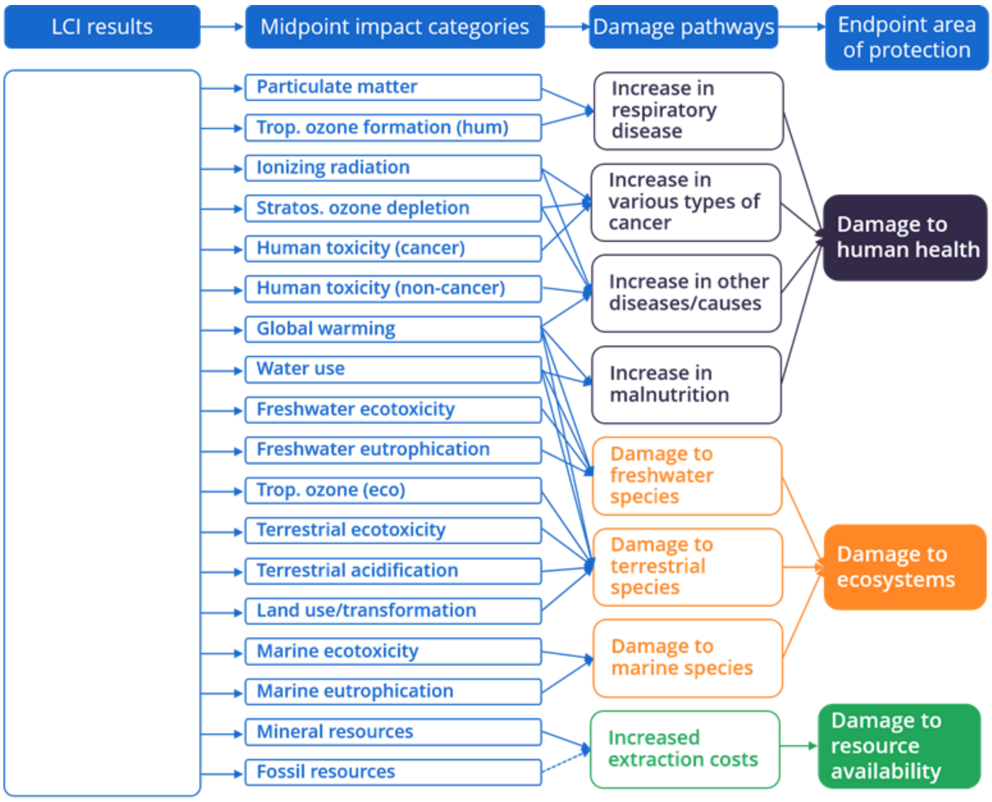

Figure 11. Midpoints and Endpoints according to the ReciPe method[7]

Therefore, for a comprehensive and robust analysis, midpoint indicators should be the **primary focus** due to their reliability and ability to highlight actionable improvement areas. Endpoint indicators can be reported **in addition,** for broader stakeholder communication and alignment with areas of protection.

3.5.3 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 providing 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 is 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. Similarly, a study of a particular aerospace paint or coating might additionally focus on Ecotoxicity.

3.5.4 Presentation of Results: Characterization, Normalization, and Weighting

- Results shall be presented as characterized midpoint indicators as indicated earlier in this section to ensure transparency and traceability.
- Normalization (e.g., comparing to regional or global averages) may be applied for awareness and educational purposes but should not replace characterized results.
- As outlined in ISO 14044, weighting should not be used in comparative assertions. Characterized results should therefore remain the primary reporting format, especially when reporting externally.
- Weighting (aggregating indicators into a single score) shall be restricted to internal trade studies and, if applied, the weighting factors and sensitivity analyses shall be documented and communicated.

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 and not normalized, results, assessments can be communicated more effectively among peers, promoting data sharing and collaboration within the industry.

3.5.5 Other criteria to include for better value chain stakeholder integration

In addition to the main results in the form of characterized midpoint indicators, supplementary data, 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. supplier to system integrator), 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. The interface format should include:

- System boundaries, functional units, and allocation rules
- Lifecycle stage coverage relevant to each stakeholder's responsibility
- Data quality requirements (source, representativeness, uncertainty)

IAEG WG12 is working on development of a template to allow for better stakeholder participation in LCA that contains many of these elements.

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 8 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 8. 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!

4.2.3 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.

4.2.4 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 9***.** 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 9. 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	✓
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/business model
**** 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**

4.3 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.

4.4 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 section provides standardized recommendations on how to structure, present, and leverage results in LCAs within the aerospace industry. Results shall be communicated in a way that is both transparent and actionable, ensuring credibility with stakeholders and usability across design, supply chain, and corporate decision-making.

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. It is an essential step to guarantee the accuracy of the analysis conducted. As stated in ISO 14044:20061, the critical review process shall ensure that:

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

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

Note that a critical review can neither verify nor validate the goals that are chosen for an LCA by the commissioner of the LCA study, nor the ways in which the LCA results are used.

6.2 Selection of the reviewers

Depending on the goal and intended audience of the LCA, internal or external independent expert should be selected to perform the review. In case of a panel of reviewers, an external independent should be selected to act as a chairperson of the review panel.

According to Annex B of ISO 14071:2024[21], a self-declaration regarding the reviewer's independence and competencies may be requested. The reviewer shall declare their competencies and knowledge in the following areas:

- ISO 14040 and 14044;
- LCA methodology and practice;
- Critical review practice;
- Relevant scientific background that allows proper interpretation of the LCA results;
- Environmental, technical and other relevant performance aspects of the product system(s) assessed;
- Language used in the study.

For the aerospace sector, especially given the high technicality of activities involved, it is recommended to emphasize on the "environmental, technical and other relevant performance aspects of the product system(s) assessed". 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.

In order to prevent possible conflicts of interest between a consultant and the contracting company within the critical review process, in the case where the LCA is performed by an external entity (consultant), the fees must be established and paid between the contracting company and the reviewer, and any possible conflicts of interest avoided. The reviewer entity must be distinct from the contracting company and/or consultant performing the LCA.

6.3 Critical review process

The critical review may be performed concurrently with, or at the end of, the LCA study.

Depending on the 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 is required. Critical review can be done by an internal/external expert or by a panel of interested parties.

For LCAs that are not intended to be disclosed to the public, internal reviews are recommended to ensure LCA reliability & robustness. Internal reviewers should not be part of the LCA project team, and it is recommended that they be trained to critical reviews methodologies.

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

For comparative LCA, 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.

The milestones at which the reviewer may submit comments and/or recommendations are:

- Goal & scope definition;
- Inventory analysis including data collection and LCA modelling;
- Impact assessment and interpretation;
- LCA report.

The critical review statement and related comments shall be part of the final LCA report.

6.3.1 EPD verification

In the case of an LCA conducted for type III declaration (Environmental Product Declaration, in compliance with [ISO:14025]), the LCA 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

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APPENDICES

Appendix A: LIFECYCLE ASSESSMENT Introduction

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 introduction to LCA 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

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 10. 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 Leveraging LCA Results for Decision-Making

LCA results are not only intended for reporting purposes, an LCA study can have many purposes as outlined in Appendix B. The different use cases, mean that the results of an LCA study can be actively applied to support sustainability strategies within aerospace companies. Potential applications include:

a) Design & Engineering

- Results to be integrated into design reviews and trade-off studies (e.g., material selection, lightweighting, modularity, design-for-disassembly).
- LCA-derived KPIs should be linked to design milestones and technology readiness levels.

b) Supplier Engagement

- Suppliers could provide product carbon footprint (PCF)/LCA data at the component level to enable better supplier choice.
- LCA results may be included in sourcing criteria and RFQs (Request for Quotation) to encourage sustainable supply chains.

c) Operations & Fleet Management

- Results can highlight operational hotspots (an energy hungry process, an opportunity to change cleaning fluid).
- Results may inform fleet-level optimization strategies, eco-routing, and retrofit programs.

d) Corporate Reporting & Strategy

- Aggregated LCA results can be aligned with industry-level frameworks such as ICAO CORSIA, and EU CSRD.
- LCA outcomes could be incorporated into annual sustainability reports and internal scorecards.

e) Regulatory & Certification Alignment

- Standardized LCA outputs can be used to demonstrate compliance with regulatory requirements (e.g., EPDs, PCF)
- Results may be leveraged to support harmonization across global regulatory regions.

A.2.2.1 LCA results for KPI development

To support comparability and transparency across organizations, LCA results could be incorporated as KPIS into a company's decision making process. A set of examples of such KPIs is included in Table 11.

Table 11. Example KPIs derived from LCA results or activities

Category	**Example KPIs**	**Application**
Climate & Energy	Carbon footprint per functional unit (e.g., kg CO_2-eq/seat-km) Energy intensity per part or subsystem (MJ/kg)	Fleet strategy, product benchmarking
Circularity & Materials	% recycled content Recyclability rate Design-for-disassembly index	Eco-design reviews, supplier engagement
Air Quality	NOx, SOx emissions per flight hour PM emissions at airports	Local community impacts, regulatory reporting
Resource Use	Critical raw materials intensity (kg/part) Fossil resource depletion (MJ) Water footprint (m^3)	Supply chain resilience, substitution analysis
Improvement Tracking	% reduction vs baseline product % of suppliers providing LCA/PCF data	Progress monitoring, target alignment

A.2.2.2 Results Interpretation & Visualization

Proper interpretation of results is critical to avoid misrepresentation and ensure informed decision-making:

- Results shall be evaluated in the context of the study goal, scope, and system boundaries.
- Limitations and assumptions (e.g., data gaps, cut-off rules, allocation choices) shall be clearly communicated alongside results.
- Comparative results (e.g., between products or technologies) shall be presented only if the study complies with ISO 14044 requirements for comparative assertions.
- Results should be supplemented with sensitivity or uncertainty analyses to demonstrate robustness.
- When communicated externally, results shall not be reduced to a single score or oversimplified metric, as this can obscure trade-offs and lead to misinterpretation.
- Clear messaging should be provided on how results inform next steps (e.g., material substitution, supplier dialogue, design iteration).

Results can be communicated through clear visualization formats tailored for different stakeholder audiences such as:

- **Engineering dashboards** (trade-off curves, material hotspot analysis)
- **Circularity diagrams** (material recovery and reuse potential)
- **Executive scorecards** (product-level LCAs rolled up to corporate net-zero targets)
- **Supply chain heatmaps** (emissions or raw material hotspots by tier)

A.2.3 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 12*, whereas in LCA product level studies they are generally referred as foreground and background systems with upstream and downstream activities

Figure 12. 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 commercial and defense aviation 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	★ (green)	★ (green)	★ (green)	★ (green)	★ (green)	★ (green)	★ (green)	★ (green)
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)	★ (purple)	★ (purple)	★ (purple)	★ (purple)	★ (purple)	★ (purple)	★ (purple)	★ (purple)

Recommended Functional Units

★ (green) 1 vehicle per flight-training hour over vehicle life
★ (purple) 1 vehicle per completed mission over vehicle life