A Parametric Life Cycle Approach for Circular and Sustainable Aircraft Design

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RESEARCH

A Parametric Life Cycle Approach for Circular and Sustainable Aircraft Design

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Abstract

In the transition toward clean aviation, assessing sustainability across the full life cycle of aircraft is essential. This study presents a parametric Python-based tool integrating Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to support circular design applied to passenger aircraft. The model enables cradle-to-grave evaluation of environmental and economic impacts, in line with ISO 14,040/44 standards, and allows the inclusion of detailed data on materials, fuel use, structural components, and end-of-life processes. The tool aims to guide design decisions by balancing environmental performance, economic feasibility, and—prospectively—social considerations. Results confirm the value of integrated life cycle methodologies in reducing aviation's footprint, and highlight the need for richer datasets and the potential role of AI in design optimization. Expanding the model to include social impact metrics represents a promising next step for truly holistic sustainability assessments in the aviation sector.

Keywords Model Based Systems Engineering · Life Cycle Assessment · Life Cycle Cost · Clean Aviation · Circular Design · Design for Sustainability

1 Introduction

The aviation industry faces increasing pressure to mitigate its environmental impact, as the global air transport demand is continuously growing up. Aircraft operation contributes significantly to climate change through emissions of CO_2, NO_x, SO_x, water vapor, soot, and the formation of contrails and cirrus clouds, all of which contribute to radiative forcing [1]. Since the seminal IPCC report Aviation and the Global Atmosphere [2], the sector has been under intensified scrutiny, prompting the adoption of regulatory measures, such as the European Union Emission Trading Scheme (EU ETS) and, more recently, initiatives aligned with the European Green Deal. Despite the continuous technological progress in propulsion systems, materials, and operational efficiency, several studies indicate that the overall environmental footprint of aviation is expected to increase unless deep, systemic changes are adopted at both the aircraft and system levels [3].

In this context, interest in quantitative sustainability assessment tools has rapidly increased. Particularly, the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are widely recognized as robust methodologies to evaluate environmental and economic impacts across the full aircraft life cycle, from raw material extraction and processing to system operation and end-of-life [4]. Those approaches are essential to avoid burden shifting between lifecycle phases and to support evidence-based decision-making. However, although LCA and LCC are well established, their integration within the early stage of engineering design activity remains limited, especially in some complex sectors, such as aerospace.

At the same time, the aerospace industry is increasingly adopting the Model-Based Systems Engineering (MBSE) to manage system complexity, ensure traceability, and support digital engineering pipelines. The SysML artifacts, such as Block Definition Diagrams (BDD) and Internal Block Diagrams (IBD), provide a natural structure to represent system

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architectures and information flows. Nevertheless, sustainability metrics are still rarely embedded in a systematic and traceable manner within the MBSE frameworks, and practical demonstrations of an integrated MBSE–LCA–LCC approach remain scarce in the literature [5].

From a design perspective, this gap is crucial. Recent studies have highlighted the need to introduce sustainability and circular design considerations from the earliest design stages and to exploit MBSE as a structured support for their integration into system life-cycle development. In this context [5], proposes a proxy-based LCA approach within MBSE for comparing circular strategies at concept stage [6], focuses on MBSE implementation at subsystem level in the aerospace domain, and [7] provides a broader methodological roadmap for the integration between systems engineering and circular design. In parallel, qualitative eco-design tools such as the LIDS Wheel [8] and Eco-checklists [9] can support requirement elicitation, but they do not provide a sufficiently quantitative basis for early trade-off analyses in complex systems. Against this background, the novelty of this paper lies in a practical parametric framework that integrates both LCA and LCC within the same MBSE-supported workflow, applied to a representative aircraft use case and to a critical subsystem, namely the landing gear. Moreover, the proposed framework is consistent with a circular design perspective, as it promotes the consideration of environmental impacts and life-cycle aspects from the earliest design phases.

The objective of this work is therefore to demonstrate how LCA and LCC tools can be practically integrated within an MBSE framework, using SysML to structure sustainability-related information and decision flows. The proposed approach is illustrated through a representative aerospace use case involving the Airbus A320 aircraft and one of its critical subsystems, i.e. the landing gear. By embedding sustainability metrics directly into BDD and IBD diagrams, the paper shows how environmental and cost indicators can be linked to system architecture, thereby enabling trade-off analyses in the early stages and supporting a more holistic evaluation of future aviation technologies.

The remainder of the paper is organized as follows: Sect. 2 presents the use case-driven methodological framework and toolchain; Sect. 3 details the MBSE and LCA/LCC implementation; Sect. 4 discusses the results obtained for the selected case study; and Sect. 5 outlines benefits, limitations, and future developments.

2 Use Case–Driven Methodological Framework

The proposed framework is developed and demonstrated through a representative clean aviation use case, being selected to reflect the challenges faced in the early-stage aircraft design, while remaining compatible with parametric life-cycle modeling.

2.1 Aircraft Use Case and System Boundaries

The primary use case consists of a single-aisle commercial aircraft, representative of the Airbus A320 class, analyzed at both aircraft and subsystem levels. This dual-scale approach allows sustainability impacts to be assessed at system level, while preserving traceability down to individual components. Among the aircraft subsystems, the landing gear is selected as a detailed secondary use case, due to its structural relevance, high material intensity, and strong coupling between mass, cost, and operational fuel consumption.

To demonstrate the capability of the framework to support multi-level sustainability assessments, the landing gear subsystem is isolated for detailed analysis. Its representation through the SysML language includes explicit material breakdown and interfaces with the aircraft operational model, allowing the evaluation of indirect effects, such as fuel penalties induced by mass variations.

This subsystem-level modelling illustrates how local design choices propagate to aircraft-level environmental and economic indicators, a key requirement for circular design and for avoiding sub-optimization at component level.

The system boundaries are defined according to a cradle-to-grave perspective as shown in Fig. 1, including:

- raw material extraction and processing,
- component manufacturing,
- aircraft operation,
- end-of-life (EoL) treatment.

Figure 1 provides a conceptual overview of the proposed integration of MBSE, LCA, and LCC throughout the main lifecycle stages of the aircraft. The left side of figure represents the progression from product development and manufacturing to operation and decommissioning, highlighting the continuity of model-based support activities across these phases. More specifically, it shows how customer expectations and design rules influence the initial design process, from basic design to detailed design synthesis, and how M&S tools (Modeling and Simulation) and V&V activities (Verification and Validation) support the transition toward implementation and manufacturing. The PLD block refers to the Product Lifecycle Development

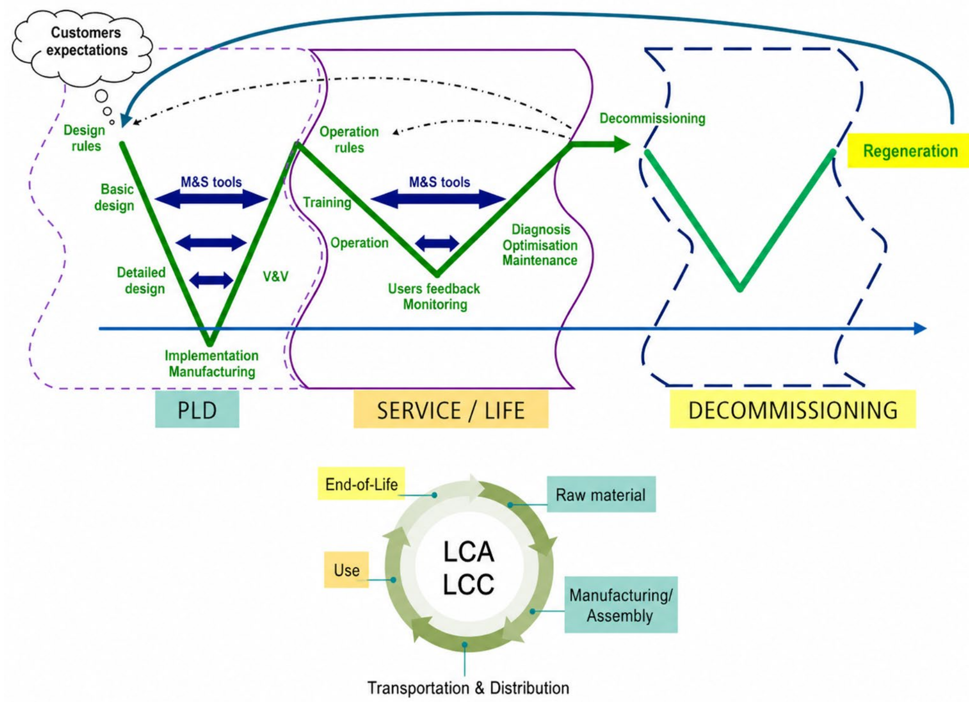

Fig. 1 – Conceptual integration of MBSE, LCA, and LCC

Phase, which precedes the service-life stage. During the service life, the same model-based logic is extended through training, operation, and users' feedback monitoring, while diagnosis, optimization, and maintenance contribute to the operational update of the system representation. The final phase of decommissioning is then connected to regeneration strategies, consistently with a lifecycle-oriented and circular design perspective.

The right side, instead, synthesizes the lifecycle assessment perspective adopted in this work, connecting raw material extraction, manufacturing and assembly, use, transportation and distribution, and end-of-life within a circular framework. In this way, the figure clarifies how environmental and economic assessments are embedded within the broader system lifecycle. Both dimensions are addressed through the combined application of LCA and LCC, following ISO 14,040/44 principles. The methodological objective is to enable parametric, traceable, and design-oriented sustainability assessments that can be performed consistently during early design phases.

2.2 Integrated LCA–LCC Approach for Aircraft Design

Within the proposed framework, LCA and LCC are treated as complementary tools, jointly supporting decision-making rather than being applied as separate post-design evaluations. Environmental indicators (e.g., Global Warming Potential) and economic indicators (lifecycle costs) are computed coherently across the same system architecture and lifecycle assumptions.

This integration allows designer to:

- perform the trade-off analysis between environmental and economic performance,
- identify sustainability hotspots across lifecycle phases,
- enable the systematic consideration of trade-offs between manufacturing, operation and end-of-life phases.

A Python-based parametric tool was developed to implement the LCA/LCC calculations. The tool enables modular definition of lifecycle phases and allows the inclusion of detailed data on materials, structural components, fuel use, and EoL scenarios. Its parametric nature supports rapid scenario analysis and sensitivity studies, which are essential in early-stage aircraft design.

Since detailed lifecycle inventories are generally not available during early design phases, the proposed tool relies on a parametric representation of the system based on the level of information typically accessible at that stage. The required inputs are derived from preliminary mass estimates, material allocations, reference emission and cost factors, fuel-burn assumptions, and end-of-life scenarios obtained from literature sources, engineering assumptions, and subsystem-level proxies. These data can be then progressively refined as the design matures, making the framework suitable for preliminary trade-off and sensitivity analyses under incomplete knowledge conditions.

Table 1 summarizes the main information families handled by the parametric tool during the early design stages. Material-related inputs are used to estimate manufacturing impacts, operational inputs describe the assumptions associated with the use phase, end-of-life inputs define recovery and disposal scenarios, and economic inputs collect the cost factors required for the LCC evaluation. In this way, the table provides a synthetic overview of the main inputs and outputs managed by the framework.

2.3 MBSE as a Structuring Layer for Sustainability Data

The integration of LCA and LCC within the design process is achieved through a Model-Based Systems Engineering (MBSE) framework, implemented resorting to the SysML language. MBSE provides the structural backbone required to manage system complexity, ensures traceability, and consistently propagates sustainability-related information across system levels.

In particular:

- Block Definition Diagrams (BDD) are used to represent the hierarchical decomposition of the aircraft into major systems and subsystems, including material and mass attributes relevant for lifecycle modelling.
- Internal Block Diagrams (IBD) describe the interactions and flows (mass, energy, information) that influence environmental and economic impacts.

Environmental and cost-related parameters are embedded directly within SysML blocks as properties, enabling a direct link between system architecture and sustainability metrics. This approach allows sustainability considerations to be treated as core design drivers, on par with traditional performance metrics.

3 Framework Implementation and Toolchain

This section describes how the use case introduced in Sect. 2 is implemented in practice, detailing the MBSE modelling approach, the parametric LCA/LCC tool, and the data flow, between system architecture and sustainability assessment.

Table 1 – Main inputs and outputs of the LCA/LCC tool

Category	Inputs	Outputs
Materials	Mass, type, emission factors	GWP, resource use
Operation	Fuel burn, flight cycles	CO_2, NO_x emissions
End-of-Life	Recycling rates, disposal	Residual impacts, credits
Economics	Cost factors	LCC breakdown

The focus is on implementation aspects that enable traceability, modularity, and scenario analysis.

3.1 SysML Modeling of the Aircraft Use Case

The aircraft and subsystem architectures are modelled using SysML, which provides a structured and formal representation of system decomposition and interfaces. The Block Definition Diagram (BDD) defines the hierarchical breakdown of the aircraft into major systems (e.g., fuselage, wing, landing gear, systems), while Internal Block Diagrams (IBD) capture the relationships and flows relevant to sustainability modelling.

Within the SysML model, each block is enriched with attributes required for LCA and LCC, including:

- mass and material composition,
- manufacturing process indicators,
- operational relevance (e.g., mass-dependent fuel contribution),
- end-of-life parameters (e.g., recycling rates).

This approach ensures that sustainability-related data are embedded directly within the system architecture, enabling full traceability between design choices and lifecycle impacts.

The aircraft and subsystem architectures are modelled using SysML, which provides a formal representation of system decomposition and interfaces. In particular, the BDD defines the hierarchical breakdown of the aircraft into major systems, while the IBD describes the relationships and flows relevant to sustainability modelling. Within this framework, each block is enriched with the attributes required for LCA and LCC, such as mass and material composition, manufacturing process indicators, operational relevance, and end-of-life parameters. This allows sustainability-related information to be embedded directly within the system architecture, ensuring traceability between design choices and life-cycle impacts. In this context, Fig. 2 illustrates the structural view of the aircraft system within its operational context, highlighting its hierarchical decomposition into the main subsystems and the further breakdown of the landing gear into lower-level components. Figure 3 complements this representation by providing the functional view of the landing gear assessment, showing the main analysis blocks implemented in the Python-based parametrisac tool together with the corresponding input and output flows. Taken together, these figures clarify how lifecycle-related information is first structured in the MBSE model and subsequently transferred to the computational workflow for LCA/LCC evaluation.

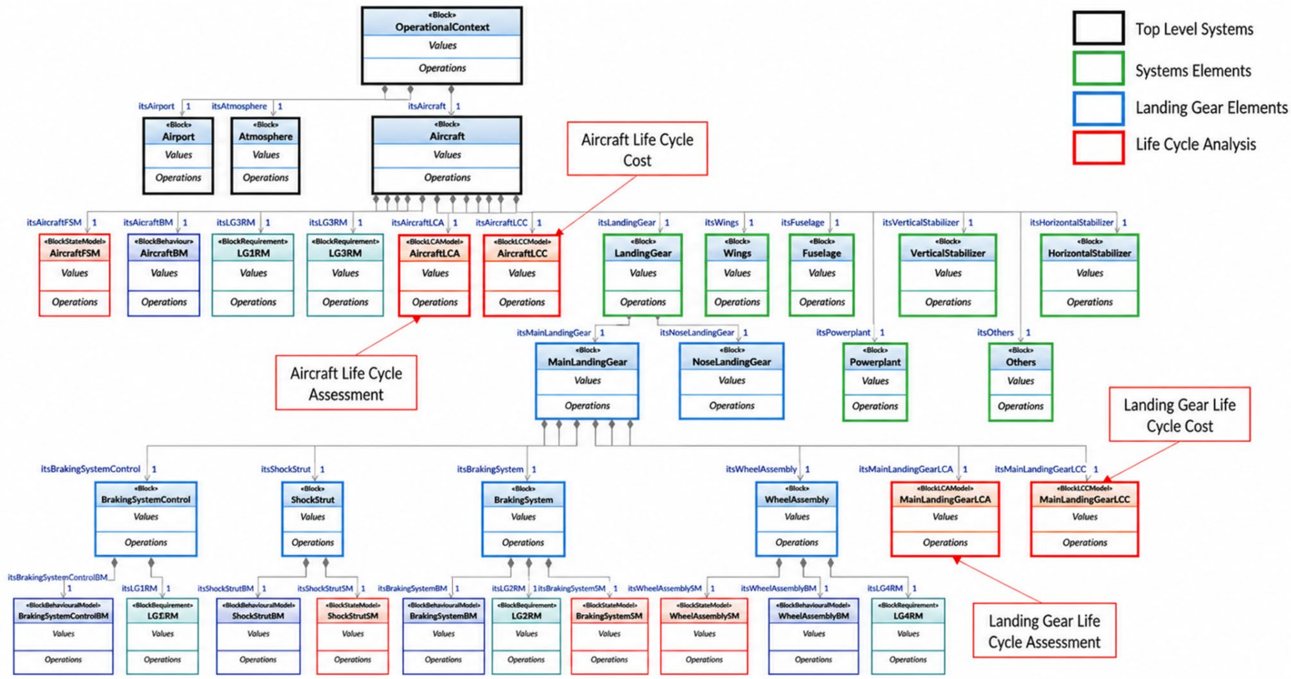

Fig. 2 SysML Block Definition Diagram of the aircraft use case with embedded sustainability attributes

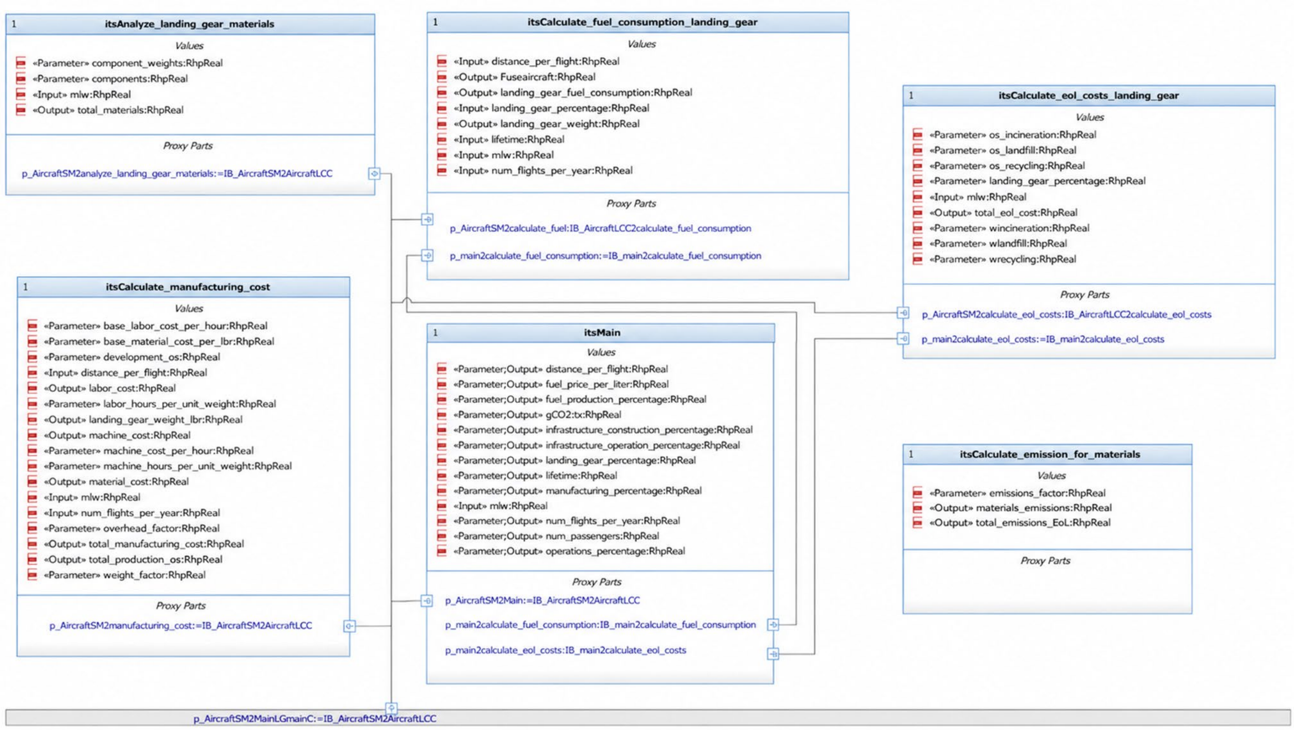

Fig. 3 Internal Block Diagram of the landing gear subsystem highlighting mass and impact propagation

3.2 Parametric LCA/LCC Computational Model

The SysML model is coupled with a Python-based parametric LCA/LCC tool that implements lifecycle calculations consistently with the ISO 14,040/44 standards. The tool is designed to mirror the system decomposition defined in SysML, ensuring one-to-one correspondence between model blocks and lifecycle inventory elements.

For each system or subsystem, the tool processes:

- manufacturing impacts, based on material mass, emission factors, and process energy demand;
- operational impacts, primarily driven by fuel consumption over the aircraft service life;
- end-of-life impacts, including recycling, disposal, and potential credits.

The parametric structure allows a rapid modification of inputs, such as material selection, mass distribution, energy mix, and EoL scenarios, enabling sensitivity analyses and comparison of alternative design options.

Table 2 reports the mapping between the main SysML blocks and the corresponding LCA/LCC.

inventory elements used in the computational workflow. The table highlights the traceability between system-level entities and the related environmental and economic inputs and outputs, while the complete set of attributes remains embedded in the SysML model and is processed through the parametric Python implementation.

3.3 Integration of LCA and LCC within MBSE

In practical terms, this integration is achieved by associating environmental and economic attributes with the same SysML entities and evaluating them under common system boundaries and lifecycle assumptions. In this way, a local design modification at subsystem level, such as a variation in landing gear mass or material composition, can be consistently propagated to manufacturing, operation, and end-of-life assessments, while also affecting the corresponding lifecycle costs. This aspect is particularly relevant in early design phases, where subsystem-level choices may generate conflicting effects between environmental and economic targets. Since the numerical implementation relies on multiple parametric routines and scenario-dependent assumptions, the present paper focuses on the integration logic and the main data flows, whereas the full equation-level formulation lies outside its scope. This formulation supports traceable trade-off analyses and helps reduce the risk of sub-optimization within the overall aircraft system.

Table 2 – Mapping between SysML blocks and LCA/LCC inventory elements

SysML Block	Description	LCA Inputs	LCC Inputs	Output Indicators
Aircraft	Top-level system	Fuel burn, lifetime	Total ownership cost	Total GWP, Total LCC
Fuselage	Structural subsystem	Material mass, EF	Manufacturing cost	GWP (manufacturing)
Wing	Structural subsystem	Material mass, EF	Manufacturing cost	GWP + fuel penalty
Landing Gear	Mechanical subsystem	Alloy mass, EF	Manufacturing + maintenance	GWP, LCC contribution
Systems	Avionics & systems	Energy demand	Procurement cost	GWP (minor share)

3.4 Toolchain Overview and Data Flow

Figure 4 summarizes the overall toolchain, highlighting the interaction between SysML modelling and parametric LCA/LCC computation. SysML provides the structural and semantic backbone, while the Python tool performs numerical evaluations and scenario analyses.

The separation between system modelling and computation should be interpreted as a functional separation within the toolchain. While SysML defines the system architecture and the lifecycle-related parameters available for the analysis, the Python-based tool performs the corresponding LCA/LCC calculations using those inputs. Therefore, the computational layer is modular and extensible, but the results remain dependent on the selected system model, its assumptions, and its level of detail. This allows the framework to be adapted to other aircraft configurations or propulsion architectures without implying full independence between modelling and computation.

4 Results and Discussion

The aircraft-level results confirm that the operation phase dominates the total lifecycle environmental impact, primarily due to fuel consumption over the service life. This outcome is consistent with consolidated literature and reinforces the relevance of operational efficiency as a key driver for clean aviation strategies under EU ETS and Fit-for-55 targets.

Manufacturing impacts, while secondary in magnitude, remain non-negligible for structural components and are particularly relevant, when evaluated in a circular design perspective. In this context, the integrated MBSE–LCA–LCC framework enables designers to identify which subsystems contribute most to non-operational impacts, supporting targeted material and process optimization.

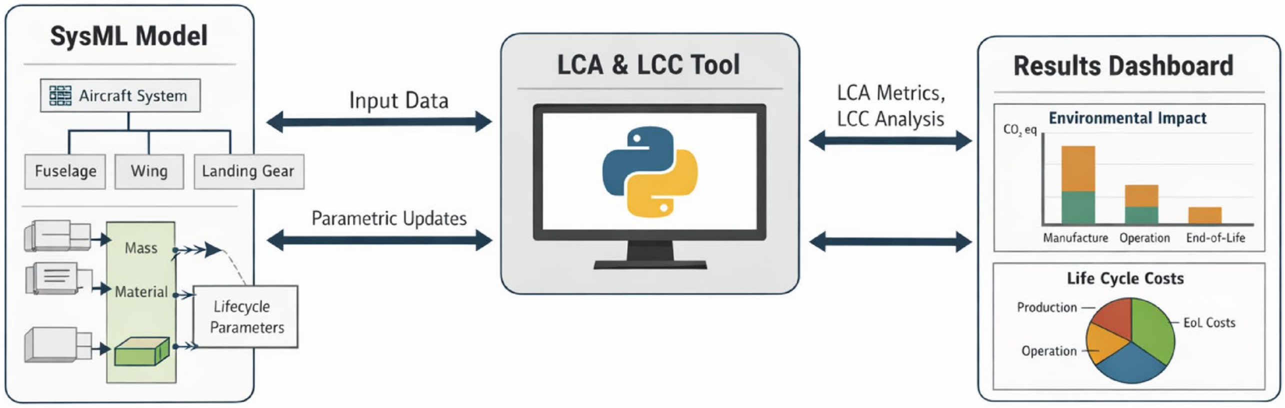

Fig. 4 Overview of the integrated MBSE–LCA–LCC toolchain enabling traceable sustainability assessment

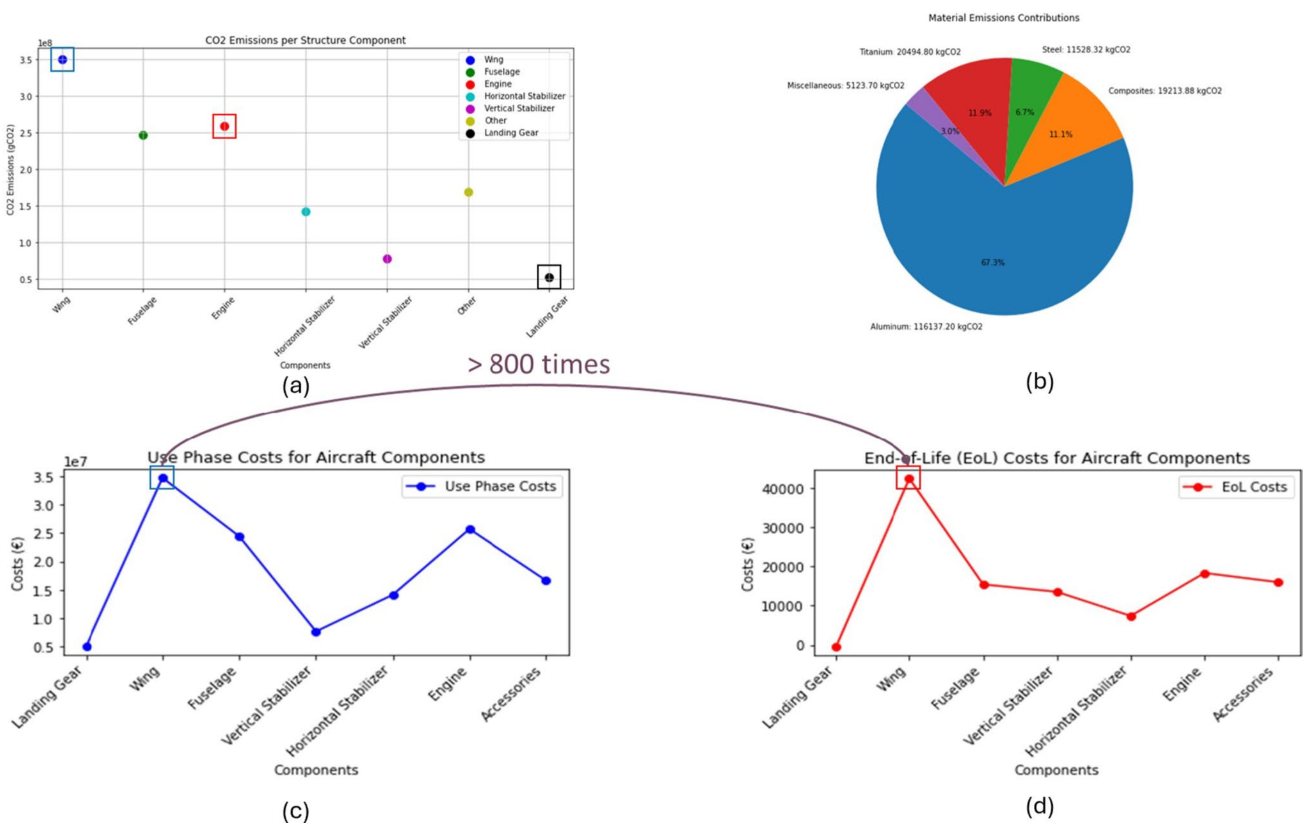

Fig. 5 (a) CO_2-equivalent emissions per aircraft component, (b) CO_2-equivalent emissions per material, (c) Use Phase and (d) End-of-Life Costs per aircraft component

From an economic perspective, the LCC results mirror the environmental trends, with operational costs representing the largest share of lifecycle costs. This alignment highlights how environmental and economic drivers are strongly coupled in aviation, and how weight-related design decisions can simultaneously affect emissions and costs.

Figure 5 illustrates the relative contribution of different components to aircraft-level CO_2-equivalent emissions and cost, along with the contribution of different materials to the CO_2-equivalent emissions.

The landing gear subsystem analysis demonstrates the added value of multi-level sustainability assessment. Although the landing gear contributes a limited fraction of total aircraft emissions, its high material intensity and structural role make it a critical subsystem for circular design considerations.

The results show that:

- material selection significantly affects manufacturing impacts,
- mass variations propagate to aircraft-level operational emissions through fuel penalties,
- subsystem-level optimization must therefore be evaluated in a system-wide context.

These findings are further supported by the detailed environmental and economic breakdowns reported in Fig. 5. In particular, Fig. 5(a) shows that the wing and engine are among the most influential components in terms of embodied CO2 emissions, whereas the landing gear remains comparatively less significant than the major structural subsystems. At material level, Fig. 5(b) identifies aluminum as the main contributor to embodied emissions, due to its widespread use across the aircraft structure, while composites also play a relevant role because of their energy-intensive production. A similar pattern emerges in the use phase, as shown in Fig. 5(c), where the components that most strongly affect aircraft mass and performance are also associated with the highest operational costs. By contrast, the end-of-life contributions reported in Fig. 5(d) remain relatively limited for all components. Those results confirm the risk of local optimization, showing that design improvements at subsystem level may lead to unintended consequences when evaluated at aircraft level. In this respect, the proposed framework enables such interactions to be explicitly captured and quantitatively assessed within a system-wide perspective.

5 Conclusions

The results obtained in this case study confirm the potential of the proposed MBSE-based LCA/LCC framework as a support tool for integrating sustainability considerations into aircraft design. However, these findings should be interpreted in light of the specific application considered in this work. Further case studies, involving different aircraft configurations and subsystem analyses, are needed to assess the generalizability, robustness, and scalability of the proposed approach across a wider range of design contexts.

Beyond the numerical results, the main contribution of this work consists in the methodological capability to support sustainability-driven design decisions in a traceable and reproducible manner. By integrating LCA and LCC within an MBSE framework, sustainability metrics become first-class design parameters rather than ex-post evaluation outputs.

This is particularly relevant in the context of clean aviation, where emerging technologies (advanced materials, new propulsion architectures) require early and transparent assessment to:

- avoid burden shifting between lifecycle phases,
- support compliance with evolving EU sustainability regulations,
- reduce the risk of qualitative or declarative sustainability claims.

The framework directly supports circular design strategies by enabling designers to explore material substitution, recycling scenarios, and architectural changes, while preserving system-level consistency. Moreover, the explicit traceability provided by SysML facilitates communication between engineering teams and supports future integration of social sustainability indicators.

Future developments will focus on:

- extending the framework to Social Life Cycle Assessment (S-LCA),
- enriching datasets for alternative propulsion systems,
- exploiting AI and machine learning to automate sustainability-driven design space exploration.

Author Contributions All authors contributed to the methodology section, E.B. defined the test case, A.S. wrote the related software and produced results, C.G. esured correspondence with ISO standards. C.G. wrote the main manuscript text and A.S. prepared figures. All authors reviewed the manuscript.

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Data Availability All data supporting the findings of this study are either available within the paper or upon request.

Declarations

Conflict of Interests The authors declare no competing interests.

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