POLITECNICO DI TORINO

Master's Degree in Mechanical Engineering

Master's Degree Thesis

Integrated Life Cycle Assessment and Life Cycle Cost Methodologies for the Development of Aeronautical Systems through 'Circular Design'

Supervisors:

Prof. Eugenio BRUSA

Prof. Chiara GASTALDI

Eng. Alberto DAGNA

Candidate:

Antonello SPAGNULO

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A mio padre

"Perché sono salito quassù? Chi indovina?"
"Per sentirsi alto".
"No. Sono salito sulla cattedra per ricordare a me stesso che dobbiamo sempre guardare le cose da angolazioni diverse. E il mondo appare diverso da quassù. Non vi ho convinti? Venite a vedere voi stessi. Coraggio! È proprio quando credete di sapere qualcosa che dovete guardarla da un'altra prospettiva".
– *Robin Williams, L'attimo Fuggente*

Abstract

Conducting a Life Cycle Assessment (LCA) requires extensive data that characterizes the product during its manufacturing, service, and end-of-life periods. It becomes evident that wide access to reliable and transparent databases is imperative for accurately modeling the system under study. Additionally, environmental processes are often very complex, necessitating the development of software tools to structure the modeled scenarios, visualize process chains, and present and analyze the results obtained. An effective LCA software should organize data, minimize the effort required for inventory analysis or impact assessment, provide documentation that validates the study, and be compatible with other software, allowing interaction between the LCA software and other tools used by LCA practitioners. This thesis explores the application of LCA as prescribed by ISO 14040/14044 standards to evaluate as primary objective the environmental impact of each phase of a passenger aircraft's service life, including manufacturing, operation, and decommissioning. To support the aircraft circular design process, incorporating both environmental and economic dimensions, and to assess the sustainability of aircraft throughout their service life, a parametric system has been implemented using a Python-based software, along with a complementary Excel file to facilitate further analysis and data management. So, the objective of this thesis, which also represents its most innovative aspect, is to develop a fully parametric model for LCA and LCC, designed with the intention of being integrated into a Model-Based Systems Engineering (MBSE) environment. Therefore, the LCA and LCC modeling is guided by the MBSE framework, where system engineering principles drive and inform the practical and numerical modeling processes. This integration ensures that the engineering system's structure dictates the analysis approach, aligning LCA and LCC with broader system design considerations. An aircraft life cycle model and framework is developed, designed to be easily extended with specific data from available literature guidelines with the potential to mitigate the aircraft's environmental impacts based on a holistic approach. This research also examines the system implementation costs and discusses potential issues and solutions. An LCA of the aircraft is conducted, considering the environmental impacts, through a cradle-to-grave methodology, of each life cycle phase, as well as the contribution of indi-

vidual aircraft structural components, different materials used, fuel consumption, and other operational processes, and finally, recycling, re-use and landfill processes. This study has demonstrated the effectiveness of integrated Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies in evaluating and improving the sustainability of aeronautical systems through "circular design." However, several areas could benefit from further research and development. Expanding the database used for LCA and LCC could enhance the accuracy and comprehensiveness of the analyses, including innovative materials and emerging technologies that would allow for a more precise assessment of environmental and economic impacts. Moreover, the integration of machine learning algorithms and artificial intelligence could further optimize the design process together with a better prediction of the long-term effects of various circular strategies. In conclusion, a potential avenue for future research could involve expanding the variety and nature of factors considered in the sustainability assessment. This expansion could allow the model to incorporate the social dimension as well. Thus, this approach can assist engineers in designing and operating more sustainable aircraft, enhancing the broader applicability of the methodologies and tools present in the aviation industry.

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Chapter 1

Introduction

1.1 The aviation industry

The rapid expansion of air travel has positioned the aviation industry as a significant contributor to human-induced climate change. The primary environmental challenges posed by the aviation sector stem from the production and burning of fossil fuels during flight operations [1, 2, 3]. Aircraft are responsible for substantial environmental damage, mainly due to air pollution from their engines.

Since the 1960s, growing environmental consciousness has led to the implementation of numerous laws and regulations, along with a surge in academic and scientific inquiry into global environmental issues. The 1999 "Aviation and the Global Atmosphere" [4] report by the Intergovernmental Panel on Climate Change (IPCC) marked a turning point, placing the aviation sector under close ecological scrutiny. From 2012 onwards, aviation became fully integrated into the European Union Emission Trading Scheme (EU ETS), marking the first international policy with binding targets to curb and control CO2 emissions from aviation. Furthermore, the European Union has committed to stabilizing CO2 levels below 450 to 550 parts per million by volume (ppmv) by 2050, guided by the 'Contraction and Convergence' framework developed by the Global Commons Institute (GCI).

Aviation emissions alter atmospheric composition, contributing to climate change, ozone depletion, and other negative environmental impacts. Specifically, aviation emissions increase the concentration of greenhouse gases (GHGs) in the atmosphere, exacerbating climate change. Besides CO2, aircraft also contribute to the radiative forcing of climate through the emission of nitrous oxides (NOx), sulfur oxides (SOx), water vapor, and soot. Other factors, such as the formation of condensation trails (contrails) and cirrus clouds, also play a role, though their environmental effects are less understood. It is projected that by 2050, aviation's contribution to total radiative forcing, excluding Aviation-Induced Cloudiness (AIC), will be approximately 4.5%, with CO_2 emissions expected to increase by a factor of 2.55 between 2002 and 2030 [5].

In recent years, the worsening environmental situation has compelled global attention towards sustainability, prompting companies and sectors to adapt their business models with a focus on environmental preservation. The future of the aviation sector will be heavily influenced by the limitations and regulations imposed by governmental institutions. Therefore, it is crucial to consider the environmental aspects of aircraft and conduct further studies to effectively address the environmental impacts of aviation. In this context, Life Cycle Assessment (LCA) emerges as an essential tool for evaluating and interpreting the environmental impacts of aircraft, serving as the premier method for environmental assessment of products.

1.2 Life Cycle Assessment

A Life Cycle Assessment (LCA), as outlined by ISO 14040/14044, evaluates the environmental impact of each phase in a passenger aircraft's life, including manufacturing, operation, and decommissioning, to determine both individual and cumulative effects. This cradle-to-grave approach was applied to the Airbus A320 to assess its environmental footprint throughout its entire life cycle, and additionally a more detailed analysis was conducted on the landing gear, as will be seen in the following chapters. LCA is a widely recognized methodology for analyzing environmental impacts and identifying key contributors, enabling informed decisions on products and services. However, LCA faces challenges, particularly in data collection, due to the complexity of tracking inputs and outputs across multiple supply chain stages. In the context of aircraft, the process is even more demanding, given the intricate construction involving millions of parts and a global supply chain. Consequently, LCA for aircraft often requires assumptions that narrow the scope of analysis, leading to potential uncertainties in the results. The complexity of assessing environmental impacts is further intensified by the involvement of numerous suppliers and customers, which complicates direct data collection. To address this, Airbus conducted a comprehensive summary analysis of the lifecycle of an aircraft, which is depicted in Fig. 1.1.

Figure 1.1: Airbus's approach to lifecycle analysis.
(Source: ametechy.blogspot.com.)

1.2.1 Methodology and Framework

As discussed before, Life Cycle Assessment (LCA) is a well-established methodology recognized globally by industry and governmental bodies for evaluating the environmental impacts of product systems throughout their entire life cycle. It is considered the premier tool for environmental assessment due to its comprehensive approach. LCA adopts a holistic perspective, providing a detailed view of a product's environmental performance and offering a clearer picture of its true impacts on the environment.

It is an ISO-standard method that consists of four distinct phases [6]: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation, as reported in Fig. 1.2.

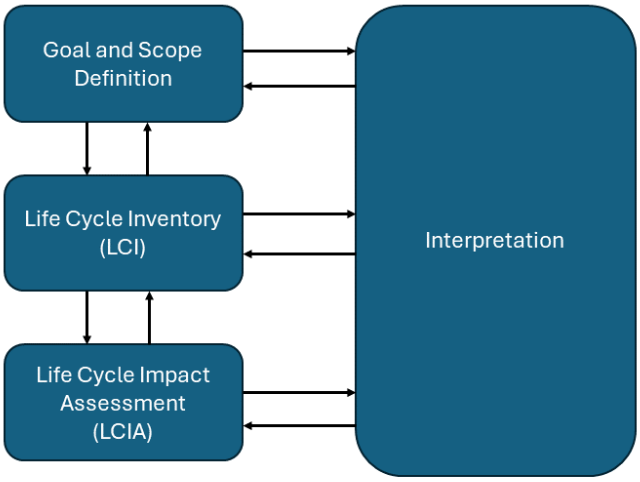

Figure 1.2: ISO-definition of LCA.

The goal and scope definition phase sets the stage by outlining the purpose and methods for integrating life cycle environmental impacts into decision-making. This phase addresses key questions, such as the reasons for conducting the LCA, the objectives of the study, the function of the product, and the intended audience for the results.

During the scope definition, it is essential to establish the study's boundaries, including the entire production process and the final disposal of materials and services involved in the product life cycle. This phase also involves specifying a functional unit, which serves as a measure of the product's function and provides a basis for the Life Cycle Inventory results. The functional unit allows for comparisons between different products, provided they share the same unit of measurement.

In the LCI phase, data on emissions and resource usage are compiled. This data is then classified and characterized into distinct environmental impact categories during the LCIA phase. Although LCA offers a robust framework for analyzing every stage of a product's life cycle and is grounded in scientific principles such as mass and energy conservation laws, it often requires substantial resources, time, and specialized knowledge. These demands can affect its widespread acceptance for engineering decision support.

Despite its advantages, LCA faces challenges, including extensive modeling requirements, data uncertainty, and parameter variability. These issues can complicate its application in engineering contexts. To overcome these challenges and enhance the evaluation of future technologies, a Life Cycle Engineering (LCE) modeling approach utilizing integrated multidisciplinary models can improve the understanding of the system's technical characteristics, components, and their associated impacts.

So the primary goal of LCA is to assess the environmental impact of a process, product, or service, thereby aiding in the selection of the most sustainable options with minimal negative effects on human and environmental health. A well-defined goal and scope ensure that the study's results meet its objectives and have a meaningful impact throughout all subsequent phases of the LCA process.

Typically, Life Cycle Assessment (LCA) does not encompass the economic and social dimensions of a product. As a result, designers often refrain from making final decisions based exclusively on LCA findings. Therefore, integrating LCA with supplementary economic analysis tools is vital. One of the most widely used methods for this purpose is Life Cycle Costing (LCC), which will be explored in the following paragraph. The main development areas of this thesis are highlighted in Fig 1.3 and will be further elaborated in the next chapters.

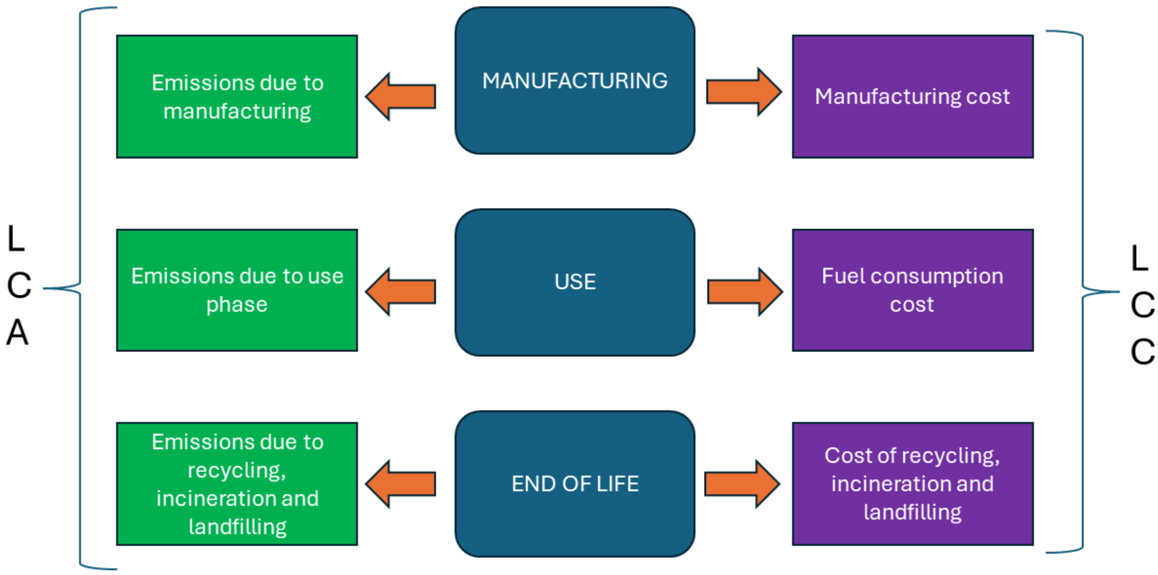

Figure 1.3: Scheme of LCA and LCC approaches.

1.3 Life Cycle Costing

From the very beginning of aircraft design, estimating costs has been a significant part. Reliably estimating the total cost of an aircraft program is critical to prevent future investments from being albatrosses. As a result, the cost aspect of aviation has been discussed widely over the past few decades.

Unlike Life Cycle Assessment (LCA), the Life Cycle Costing (LCC) methodology offers monetary insights when fully integrated with life cycle inventory [7]. This integrated model simplifies environmental assessments and makes the interpretation of results more accessible for the intended audience. Expanding LCA to include LCC systematically could drive industrial practices toward more sustainable design choices.

The primary aim of LCC is to evaluate costs at every stage of a product's life cycle, including those not reflected in the market price, such as costs related to usage and disposal. LCC is particularly valuable when selecting the most cost-effective option from a range of alternatives. The methodology accounts for all internal and external costs associated with a product's life cycle. Internal costs are those borne by the company over a specific period, such as production, transportation, usage, and end-of-life expenses, directly impacting stakeholders like producers, transporters, and consumers.

On the other hand, external costs are not directly paid by the company, consumer, or government involved in the product's lifecycle. These costs include the depletion of natural resources, impacts on human health, ecological consequences, and effects on infrastructure and buildings. They represent the monetized outcomes of environmental and social impacts that are not regulated or assigned to the company by the market or government.

In economic assessments, various methodological approaches exist for calculating costs and performance metrics [8]. In line with LCA, the LCC methodology quantifies economic factors throughout the entire life cycle by summing all associated costs and benefits, thereby identifying potential economic hotspots. The Society of Environmental Toxicology and Chemistry (SETAC)—Europe Working Group on Life Cycle Costing defines three types of LCC, each differing in the scope of external costs considered: conventional LCC, environmental LCC, and societal LCC [9].

Conventional LCC focuses on internal costs that are directly covered by the producer or user. These costs include materials, energy, labor, equipment, and overheads, and the analysis typically views the product from the perspective of a single market actor, such as the manufacturer or customer, without separate LCA results. Environmental LCC expands this scope to include costs borne by multiple market actors across the product's life cycle, such as suppliers, manufacturers, consumers, or end-of-life handlers. Societal LCC further extends environmental LCC by incorporating additional external costs, often quantified using willingness-to-pay methods, and considers the perspective of society as a whole, including national and international governments.

1.4 Beyond LCA and LCC

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have long been the cornerstones, offering well-thought frameworks for performing the evaluation of environmental impacts and economic efficiency induced through products and services along the lifecycle. More specifically, LCA provides a holistic tool to quantify the environmental impacts of all stages of a product life-cycle, from raw material extraction to production, use and final disposal. This allows organizations and policymakers to pinpoint and address possible environmental hotspots, leading the way towards a more sustainable trajectory. Likewise, LCC serves well in embracing this aspect of environmental concern whilst providing an effective evaluation on the life cycle cost benefits of a certain product. When LCA and LCC are integrated, stakeholders are able to use the most appropriate information to optimize their decisions with respect to both environmental performance and cost.

However, as sustainability challenges grow more complex, it becomes increasingly evident that no single method can address all aspects of sustainable development. While LCA and LCC provide valuable insights, they do not encompass all the factors that influence a product's sustainability, particularly in areas such as social impact, resource efficiency, and broader environmental consequences. As a result, a variety of other approaches have been developed to fill these gaps, each offering a unique perspective on sustainability. These methodologies include Environmental Impact Assessment (EIA), Material Flow Analysis (MFA), Social Life Cycle Assessment (SLCA) and the Ecological Footprint (EF), as illustrated in Fig. 1.4 and Cost-Benefit Analysis (CBA) and Sustainable Value Stream Mapping (SVSM) as reported in Fig. 1.5.

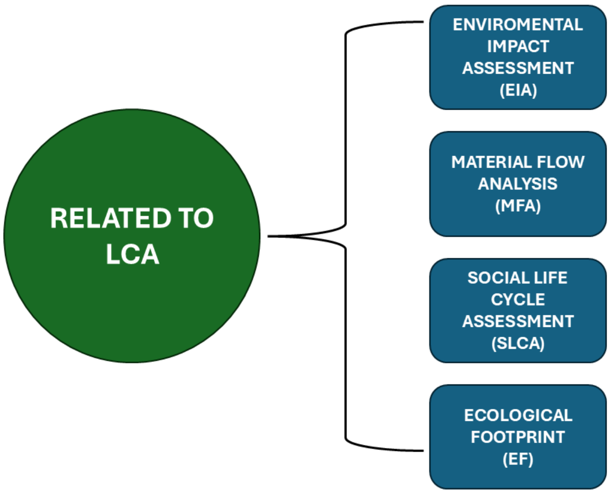

Figure 1.4: Different approaches to LCA.

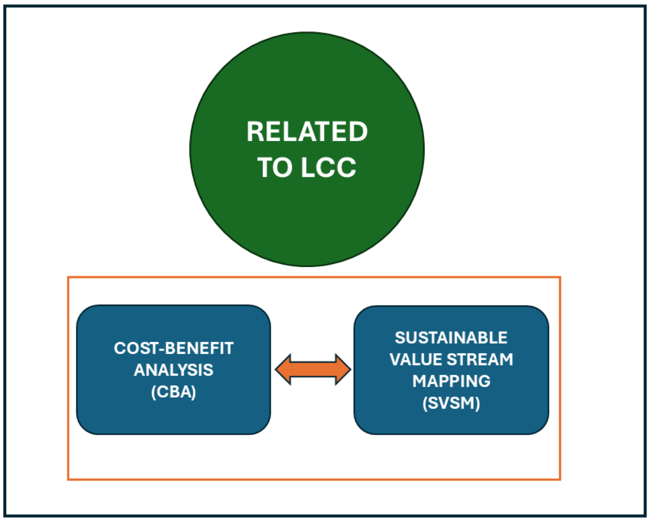

Figure 1.5: Different approaches to LCC.

These additional approaches extend the scope of traditional assessments, enabling a more comprehensive evaluation of sustainability that includes not only environmental and economic factors but also social, resource-based, and systemic considerations. By exploring these methodologies alongside LCA and LCC, we gain a richer, more nuanced understanding of sustainability that better equips us to address the multifaceted challenges of modern development. The following sections will delve into each of these approaches, examining their methodologies, strengths, and how they complement LCA and LCC in promoting a more holistic approach to sustainable development.

1.4.1 Different approaches to LCA

Environmental Impact Assessment (EIA)

Environmental Impact Assessment (EIA) is a systematic process utilized to predict the environmental consequences of proposed projects, plans, or policies before they are carried out. Unlike Life Cycle Assessment (LCA), which takes a holistic view of the entire life cycle of a product or service, EIA is focused on assessing the environmental effects of specific projects or developments, typically on a local or regional scale. The EIA process involves the identification, prediction, and evaluation of potential environmental effects, such as those on land, air, water, flora, and fauna, as well as the social and economic implications. One of the critical strengths of EIA is its role in ensuring that environmental considerations are integrated into decision-making processes, thereby preventing or mitigating potential negative impacts before they occur. Public consultation and stakeholder involvement are integral to EIA, providing transparency and enabling the inclusion of community concerns in the final assessment. However, EIA is project-specific and might not capture the broader environmental implications that LCA addresses, such as global supply chain impacts. Despite this limitation, EIA remains a vital tool for environmental management, especially in regulatory frameworks where it often serves as a prerequisite for project approval.

Material Flow Analysis (MFA)

Material Flow Analysis (MFA) is a methodological approach that quantifies the flows and stocks of materials within a defined system, such as an economy, industry, or process. The primary objective of MFA is to identify inefficiencies in the use of resources and to uncover opportunities for reducing waste, enhancing recycling, and improving overall material efficiency. By mapping out the input, throughput, and output of materials, MFA helps to understand the life cycle of resources, from extraction to disposal. This analysis is particularly valuable in identifying potential bottlenecks or hotspots where resource consumption is disproportionately high or where environmental impacts are most significant. MFA can be applied at various scales, from individual processes to entire national economies, and is often used in conjunction with LCA to provide a more detailed understanding of the material dependencies and their associated environmental impacts. One of the key advantages of MFA is its ability to highlight the flow of materials that might otherwise be overlooked, such as hidden waste streams or energy losses. By addressing these inefficiencies, industries can move towards more sustainable practices, reducing their environmental footprint and improving resource circularity.

Social Life Cycle Assessment (SLCA)

Social Life Cycle Assessment (SLCA) is an extension of the traditional LCA framework, designed to assess the social and socio-economic impacts of products and services throughout their life cycle. While LCA focuses on environmental impacts, SLCA evaluates how a product's life cycle affects various stakeholders, including workers, consumers, local communities, and society at large. This approach considers a broad range of social issues, such as labor rights, health and safety, human rights, and community well-being. The methodology of SLCA is still evolving, with ongoing debates about the best ways to quantify social impacts and integrate them into broader sustainability assessments. Unlike environmental impacts, which can often be measured in physical units (e.g., emissions, energy use), social impacts are more subjective and context-dependent, making them harder to quantify. However, SLCA provides a critical perspective on sustainability by highlighting the human dimensions of production and consumption. For businesses, SLCA offers insights into potential risks and opportunities related to social responsibility, helping them to improve their social performance and build more ethical supply chains.

Ecological Footprint (EF)

The Ecological Footprint (EF) is a measure that quantifies the amount of biologically productive land and water area required to support the consumption and waste generation of a given population, activity, or product. Essentially, it compares human demand on natural resources with the Earth's ability to regenerate those resources and absorb waste, such as carbon emissions. The EF is expressed in global hectares (gha) and is used to assess the sustainability of various activities, regions, or even entire nations. A key concept in EF is "overshoot," which occurs when humanity's demand exceeds the Earth's capacity to regenerate, leading to resource depletion and environmental degradation. While the EF provides a useful snapshot of human impact on the planet, it is a relatively coarse metric that simplifies complex interactions within ecosystems. It does not account for all environmental impacts, such as pollution or biodiversity loss, and can sometimes mask variations in resource efficiency among different regions or industries. Nonetheless, the EF is a powerful communication tool that raises awareness about the limits of Earth's resources and the need for more sustainable consumption patterns.

1.4.2 Different approaches to LCC

Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis (CBA) is an economic tool used to evaluate the total costs and benefits of a project, policy, or decision to determine its overall feasibility and desirability. In essence, CBA attempts to quantify in monetary terms all the positive and negative impacts associated with an initiative, allowing decision-makers to compare the net benefits against the costs. This method is particularly useful when there are multiple alternatives, as it provides a clear framework for comparing options based on their economic value. CBA considers both direct and indirect costs, including those related to environmental and social factors, although quantifying these latter aspects can be challenging. For example, while it is relatively straightforward to calculate the costs of construction or operation, putting a monetary value on environmental degradation or loss of biodiversity requires assumptions and estimations that may introduce uncertainty into the analysis. Despite these challenges, CBA remains a widely used tool in public policy and project planning, as it provides a rational basis for allocating resources and justifying expenditures. Its application is not limited to economic projects but extends to environmental policies, where it can be used to weigh the costs of regulatory actions against the benefits of environmental protection.

Sustainable Value Stream Mapping (SVSM)

Sustainable Value Stream Mapping (SVSM) is an adaptation of the traditional Value Stream Mapping (VSM) tool used in lean manufacturing, which focuses on identifying and eliminating waste within production processes. SVSM extends this concept by incorporating sustainability considerations, such as environmental and social impacts, alongside economic efficiency. By mapping out the entire value stream—from raw material extraction to end-of-life disposal—SVSM helps organizations identify opportunities to reduce environmental impacts, improve energy and resource efficiency, and enhance social responsibility within their operations. This holistic approach allows businesses to optimize not only for cost and productivity but also for sustainability, leading to more resilient and sustainable business practices. SVSM is particularly valuable in industries where supply chains are complex and involve multiple stakeholders, as it provides a clear visual representation of where sustainability gains can be made. By integrating lean principles with sustainability goals, SVSM supports the transition to more sustainable production systems that align with broader environmental and social objectives.

1.4.3 Literature review on EOL

The aviation industry is confronting a critical challenge as the number of aging aircraft continues to grow. Each year, approximately 400 commercial planes become obsolete, with predictions estimating that between 12,000 and 14,000 aircraft will reach their end of life within the next two decades [10]. This could lead to the decommissioning of up to 700 aircraft annually. Despite this trend, large-scale recycling of retired aircraft is still in its early stages, with limited data available due to the lack of centralized records. The Aircraft Fleet Recycling Association (AFRA) has reported that its members have successfully recycled thousands of military and commercial aircraft since 2006.

In response to this growing demand for recycling, the need for more advanced EOL management strategies is becoming increasingly urgent. The average age of retired aircraft is decreasing as newer, more efficient models replace older ones. Major manufacturers like Airbus and Boeing have recognized the importance of this issue and are actively investing in projects like Airbus' PAMELA-LIFE initiative and Boeing's founding of AFRA, both aimed at developing sustainable processes for aircraft recycling and enhancing eco-efficiency standards [11].

An aircraft's lifecycle comprises six main phases: design, manufacturing, operation, maintenance, parking/storage, and end-of-life. Historically, the EOL phase has been neglected, but as more aircraft retire, there is an increasing emphasis on optimizing designs to facilitate better dismantling and recycling. Traditionally, many retired aircraft have been stored in desert "boneyards" where favorable climate conditions slow deterioration. However, this practice poses environmental risks, as many of these planes deteriorate over time. While aircraft typically remain stored for around two years before being dismantled, over 2,000 planes are currently in storage with no clear plan for future recycling [12].

The EOL process is divided into several stages: decommissioning, disassembly, dismantling, and material recovery. Decommissioning officially removes the aircraft from service, while disassembly involves extracting valuable components such as engines and avionics, which may be recertified and resold. Dismantling follows, where the airframe is reduced to scrap to recover valuable materials. The dismantling process includes decontamination, part extraction, materials recovery, and finally, shredding. Metals like aluminum, alloy steel, and titanium are then sorted and sold to recyclers. However, quality issues often limit the reuse of these materials, resulting in downcycling where the recycled materials are repurposed for lower-grade applications, such as in the automotive or construction industries.

One of the key challenges in aircraft recycling is ensuring the effective reuse of recovered materials, especially aluminum [13]. Improving separation techniques during dismantling could allow for higher-value recycling applications. Additionally, addressing harmful substances like hexavalent chromium in aluminum scrap is vital for expanding its reuse potential [14].

The decision-making process at the end of an aircraft's service life is complex. When an aircraft's overall value outweighs the sum of its parts, it may be sold to regions with less stringent regulations. Otherwise, the plane must be dismantled and its components reused, recycled, or disposed of. Components like engines, landing gears, avionics, and interiors are the most commonly recovered, with some parts like doors and wings being repurposed for non-aeronautical uses, such as training.

Aircraft recycling involves a comprehensive approach that spans the entire EOL process, from dismantling to material recovery. Remanufacturing, where parts are restored to their original specifications, is crucial for extending component lifecycles and offering products with near-new quality. Recycling, defined as "the series of activities by which discarded materials are collected, sorted, processed, and used in the production of new products" [15] , remains a core strategy for waste reduction, though designers often hesitate to use recycled materials due to concerns about quality and supply consistency [16].

Overall, the growing number of retired aircraft calls for a more structured and sustainable approach to EOL management. By enhancing design considerations and recycling processes, the industry can improve material recovery, reduce environmental impacts, and create more eco-friendly solutions for managing aircraft disposal.

1.5 The world behind Circular Economy

The concept of a circular economy represents a systemic shift from the traditional linear economic model, where resources are extracted, used, and ultimately disposed of, as depicted in Fig. 1.6.

Figure 1.6: Circular Economy strategy.
(Source: repak.ie)

The circular economy focuses on reducing waste and extending the useful life of products through innovative practices such as recycling, reuse, repair, and refurbishment, thereby minimizing environmental impacts. The three basic principles of the circular economy are:

- Eliminate waste and pollution from the design stage
- Use products and materials as long as possible
- Regenerate natural systems

These principles are reflected in design and production processes that utilize recyclable and biodegradable materials and efficient production methods. At the same time, they promote repair, maintenance, and reuse to extend the life cycle of products.

Resource efficiency is a central pillar of the circular economy, and companies are encouraged to optimize their use of raw materials, energy, and water by adopting lean production techniques and exploring the use of more sustainable alternative materials. Waste from one industry can be converted into raw materials for another, or organic waste can be used as compost to return nutrients to the soil. This approach not only reduces environmental impact, but also stimulates new economic opportunities, such as job creation in new areas of recycling, repair, and sustainable production. In addition, the circular economy offers significant benefits in terms of economic resilience by reducing dependence on raw materials and minimizing waste, thereby increasing the resilience of businesses to market fluctuations.

From a social perspective, the transition to a circular economy can promote local economic development and create jobs, especially in communities directly affected by the production and reuse of materials. From an environmental perspective, the circular economy can contribute significantly to reducing environmental impacts by reducing pressure on natural resources and reducing greenhouse gas emissions. Renewable practices also help restore ecosystems and increase biodiversity, promoting long-term sustainability.

However, implementing the circular economy is not without challenges. There are numerous barriers to circular business model developments, including “technical barriers such as an inappropriate technology, or lack of technical support and training; economic barriers such as capital requirements, high initial costs, or uncertain return and profit; institutional and regulatory barriers such as a lack of a conducive legal system, or a deficient institutional framework; and social and cultural barriers such as a rigidity of consumer behavior and businesses routines” [17, 18]; and more of this technological barriers, such as the development of the necessary technologies to effectively recycle and reuse materials that represent a significant obstacle. Changing consumer behavior towards more sustainable practices also presents a significant challenge. Lastly, governments play a crucial role in promoting the circular economy through policies, incentives, and regulations, but the lack of uniform regulations across regions and sectors can complicate the widespread adoption of circular practices.

Despite these difficulties, the circular economy offers an innovative perspective on production and consumption, emphasizing sustainability, resource efficiency, and environmental protection. By rethinking how we design, use, and dispose of products, we can create an economy that works for both people and the planet.

1.6 Systems Engineering

The International Council on Systems Engineering (INCOSE) described Systems Engineering as "a mean to enable the realization of successful systems" and "focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem". Moreover, "it integrates all the disciplines and specially groups into a team effort forming a structured development process that proceeds from concept to production to operation". It "considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" [19]. It is immediately apparent that certain key features are inherent to the proposed approach and are even mentioned in the definition provided.

More in detail, Systems Engineering is an interdisciplinary discipline aimed at the comprehensive design and oversight of intricate systems, ensuring all elements work harmoniously to achieve defined goals. It spans the entire lifecycle of a system, from initial concept and design through to manufacturing, operation, and decommissioning. The essence of Systems Engineering lies in integrating various fields and components to produce a cohesive and effective system that meets the needs of users and stakeholders.

Model-Based Systems Engineering (MBSE) marks a transformative shift within this field by prioritizing the use of models over conventional document-centric approaches. MBSE utilizes detailed visual and mathematical representations to capture and analyze system requirements, structures, and functions. This methodology offers significant benefits, including enhanced clarity in team communication, improved handling of system complexity, and a decrease in design-related errors.

The literature highlights various contributions, particularly emphasizing the versatility of Systems Engineering. This field has proven effective across numerous industrial sectors, demonstrating its adaptability with high confidence and minimal adjustments needed for specific tasks. It fundamentally relies on a unified, systematic, and efficient methodology. Traditionally, design efforts began with rudimentary product concepts often documented in text. However, methodologies such as Model-Based Systems Engineering (MBSE) offer advanced tools to convert these documents into dynamic digital models. These models are integrated with numerical analyses and play a crucial role in the later stages of product development. Key advantages of this approach include the ability to reuse models across different projects, maintain comprehensive traceability of each requirement through its linkage to functions and system components, and automate the documentation process throughout the entire development lifecycle. By continuously refining models and simulating system performance, MBSE supports a more iterative and integrated development process, ultimately leading to higher-quality and more efficient engineering outcomes.

1.6.1 Fundamental aims and Four Pillars

According to [20], the main objectives of Model-Based Systems Engineering (MBSE) can be classified into four key areas:

1. **Effective Management of Complexity**: Modern products are increasingly intricate, consisting of numerous subsystems, components, and often incorporating advanced features like smart capabilities and communication interfaces. This complexity, exemplified by the integration of electronic control units and sensors into mechanical and electromechanical systems, challenges traditional management tools. MBSE addresses this complexity by providing robust tools for comprehensive design and analysis, accommodating each component's interactions and energy conversions.

2. **Lifecycle Traceability**: Contemporary products require extended support throughout their lifecycle, including monitoring, maintenance, and servicing. Failure to fully account for lifecycle considerations can lead to rising costs due to unforeseen post-market requirements. MBSE ensures complete traceability from initial requirements through to final part numbers, enabling thorough management and oversight of the entire product lifecycle.

3. **Creation, Digitalization, Reusability, and Automated Documentation**: Thorough and accessible documentation is essential for system operation, maintenance, and troubleshooting. MBSE supports the digitalization of

this documentation, which is then managed through centralized systems with secure access. By leveraging models rather than static documents, MBSE allows for reuse across different projects, seamless integration into various documents, and automated generation of documentation. This enhances collaboration within the organization and with external partners, such as suppliers and customers.

4. **Cost Reduction and Minimization of Errors**: Systems Engineering has become increasingly prevalent in the industrial sector due to its effectiveness in managing complex, multidisciplinary projects. MBSE facilitates this by decomposing system complexity and employing a "left shift" approach, which focuses on optimizing resource use earlier in the lifecycle. This leads to reduced development costs, fewer human errors, and decreased need for late-stage re-engineering.

To gain a deeper understanding, it's beneficial to focus on specific elements of the broader topic. Generally, the literature identifies four primary areas of interest: methodology, language, tools, and data management [20].

Methodology: Systems Engineering (SE) relies on digital models, which facilitate easy sharing among users and efficient storage through data management systems. This characteristic defines the SE approach as a "model-based" method, commonly known as Model-Based Systems Engineering (MBSE). Within this framework, two principal types of models are employed: one that guides the system engineer through the development process and addresses the product lifecycle, and another that offers both qualitative (logical) and quantitative (numerical) insights into the product as a complex system.

Tools: Implementing MBSE involves two main categories of tools. The first includes theoretical instruments such as various standard diagrams and engineering methodologies. The second category comprises software platforms that create a digital environment for applying MBSE practices using standardized languages.

Language: In SE, several modeling languages are used. Historically, the Unified Modeling Language (UML) has been a significant foundation, which was later adapted to create the System Modeling Language (SysML). However, other languages are also being developed to address the limitations of UML and SysML, especially in the context of industrial product manufacturing.

Data Management: Effective data and information management is crucial for SE. The platform must integrate with networks, whether through data buses, cloud services, or other web-based solutions. Key aspects include ensuring interoperability of software tools and maintaining robust cybersecurity.

Chapter 2

Use case 1: Airbus A320

2.1 A Comprehensive Overview of the Airbus A320

The Airbus A320 is a narrow-body, single-aisle aircraft widely used for short to medium-haul routes. It was chosen for analysis due to its extensive operational presence; with over 4,530 units in service, the A320 stands as the world's fastest-selling commercial jet. This aircraft serves as the baseline model for the A320 family and was the first civil airliner to introduce a digital fly-by-wire control system, which enhanced handling and safety—features now standard in modern aviation. Typically deployed on flights with a range of up to 6,150 kilometers, the A320 has a wingspan of 35.8 meters (including sharklets), a length of 37.57 meters, and a maximum payload capacity of 16.6 tons. Standard configurations allow seating for 140 to 170 passengers, though the aircraft can accommodate up to 180 at full capacity. Its design and size make it comparable to its primary competitor, the Boeing 737.

Airbus forecasts continued growth in the Asia-Pacific region, expecting the fleet to double by 2029, with single-aisle aircraft projected to constitute around 69 percentage of new deliveries over the next two decades.

Constructing this best-selling aircraft involves assembling approximately 340,000 parts, including 575 buttons, switches and knobs, as resumed in Fig. 2.1.

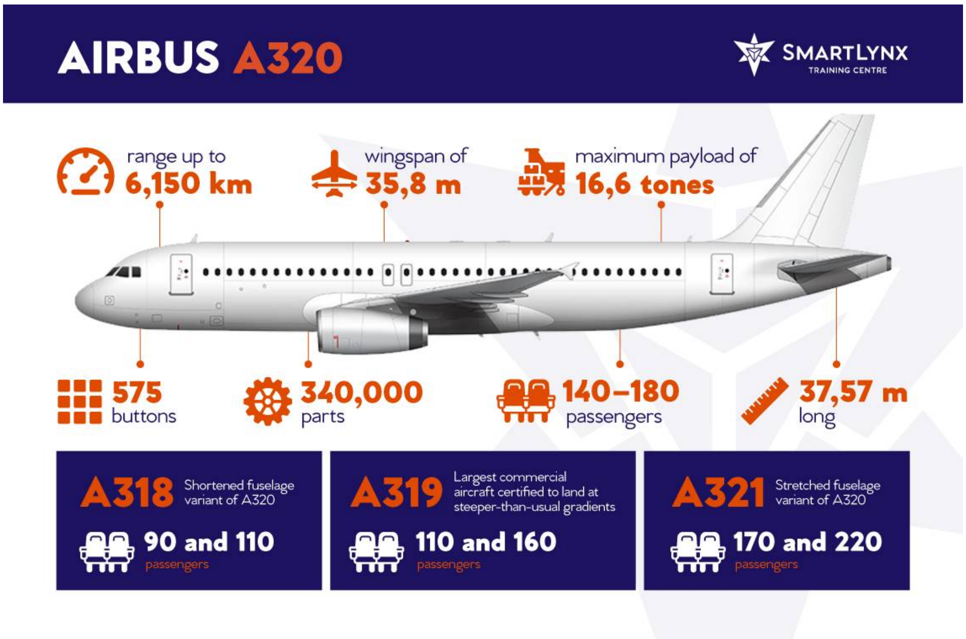

Figure 2.1: Overview of A320 aircraft.
(Source: smartlynx.aero)

As the first member of the most popular single-aisle aircraft family in the world, the A320 set a new standard in aviation. Given the immense complexity of a large commercial aircraft, which comprises millions of individual parts and components, modeling every element in detail is impractical. To streamline the study, the A320 has been divided into 7 major structural sections further broken down into 75 sub-assemblies [21]. Despite this, the analysis faces limitations, particularly regarding aircraft systems and internal components, such as cockpit instrumentation, hydraulic systems, and batteries, which are typically produced by third-party suppliers. This results in restricted access to precise data. Additionally, information on aircraft development and production is often difficult to obtain due to commercial confidentiality. Nevertheless, an overview of the basic A320 lifecycle is presented in Tab. 2.1. The final stages of the aircraft's lifecycle, including disposal options like recycling, incineration, and landfill, will be further explored in the following sections.

2.1.1 Design, Development and Lifecycle Analysis

For the case study of an A320 aircraft, as well as for the landing gear subsystem test case, three main phases have been identified and analyzed for the lifecycle (for both LCA and LCC studies): Manufacturing phase, Use phase, and End-of-Life phase (Fig. 2.2).

Component	Sub-components
Wings x2	Aileron, Flaps, Slats, Wing Box, Spoiler, Wing Tips
Fuselage	Doors, Frames, Skin, Interior, Bulkheads, Stringers
Vertical Stabilizer	Box, Rudder, Tip, Dorsal Fin, Fairings
Horizontal Stabilizer	Box, Elevator, Fairings
Powerplant x2	Powerplant Accessories, Cowlings, Pylons, Thrust Reverser, Inlet Cowl, Engine
Landing Gear	Main Landing Gear x2, LDG, Downlock, Actuator, Fairings, Wheels & Tyres, Nose LDG
Other	Flight Management System, Transpoder, Fire Extinguishers, Seats, etc.

Table 2.1: Major Structural Components and Sub-components of the Airbus A320.

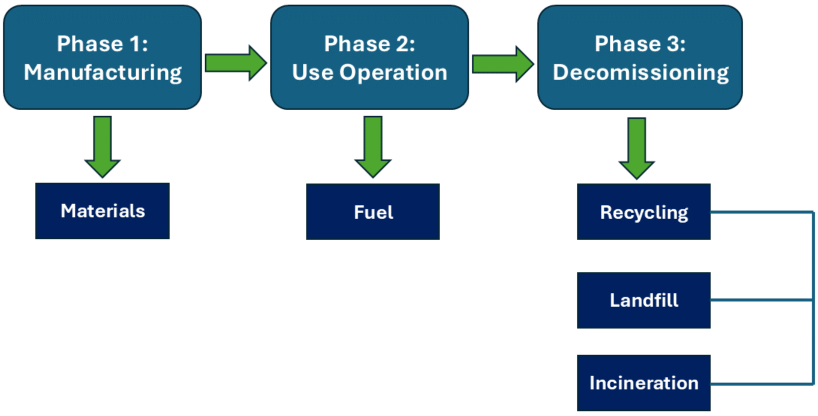

Figure 2.2: Life cycle flow diagram for A320.

Moreover, Tab. 2.2 summarizes the assumptions regarding the mass of each assembly, while Tab. 2.3 presents the proportional content of each key material in the aircraft's structure [21].

Structural Components	Mass Distribution (%)
Wings	27%
Fuselage	19%
Vertical stabilizer	6%
Horizontal stabilizer	11%
Landing gear	4%
Powerplant	20%
Other	13%

Table 2.2: Structural Components and Mass Distribution of the Airbus A320.

Structural Components	Percentage Composition (%)
Aluminum	68%
Composites	15%
Steel	9%
Titanium	6%
Miscellaneous	2%

Table 2.3: Structural Materials and Percentage Composition of the Airbus A320.

The life-cycle phases included are shown in the following Table 2.4 and are divided into 4 main groups [22]:

1. Operational components: directly related to the aircraft's operation and flight service;

2. Non-operational components: covering administrative and support actions not directly linked to flight operations;

3. Infrastructure: related to the use of physical structures and support services;

4. Fuels: concerning specific fuels used for flight operations.

Operational Components	Non-Operational Components		
VEHICLE ACTIVE OPERATION	VEHICLE INACTIVE OPERATION	VEHICLE MANUFACTURING	VEHICLE MAINTENANCE
Take Off	Auxiliary Power Unit Operation	Aircraft Manufacturing	Aircraft Maintenance
Climb out	Startup	Engine Manufacturing	Engine Maintenance
Cruise	Taxi out		
Approach	Taxi in		
Landing			
Fuels			
FUEL PRODUCTION			
Jet fuel refining and distribution			
Infrastructure			
INFRASTRUCTURE CONSTRUCTION	INFRASTRUCTURE OPERATION	MAINTENANCE	VEHICLE PARKING
Airport construction	Runway lighting	Airport maintenance	Airport parking
Runway/taxiway/tarmac construction	Deicing fluid production		
	Ground support equipment operation		

Table 2.4: Lifecycle Phases

Fig. 2.3 depicts a block definition diagram (BDD) in SysML (Systems Modeling Language) and used in systems engineering and modeling. This diagram represents a hierarchical structure of an aircraft and its subsystems, with various blocks symbolizing different components and aspects of the aircraft.

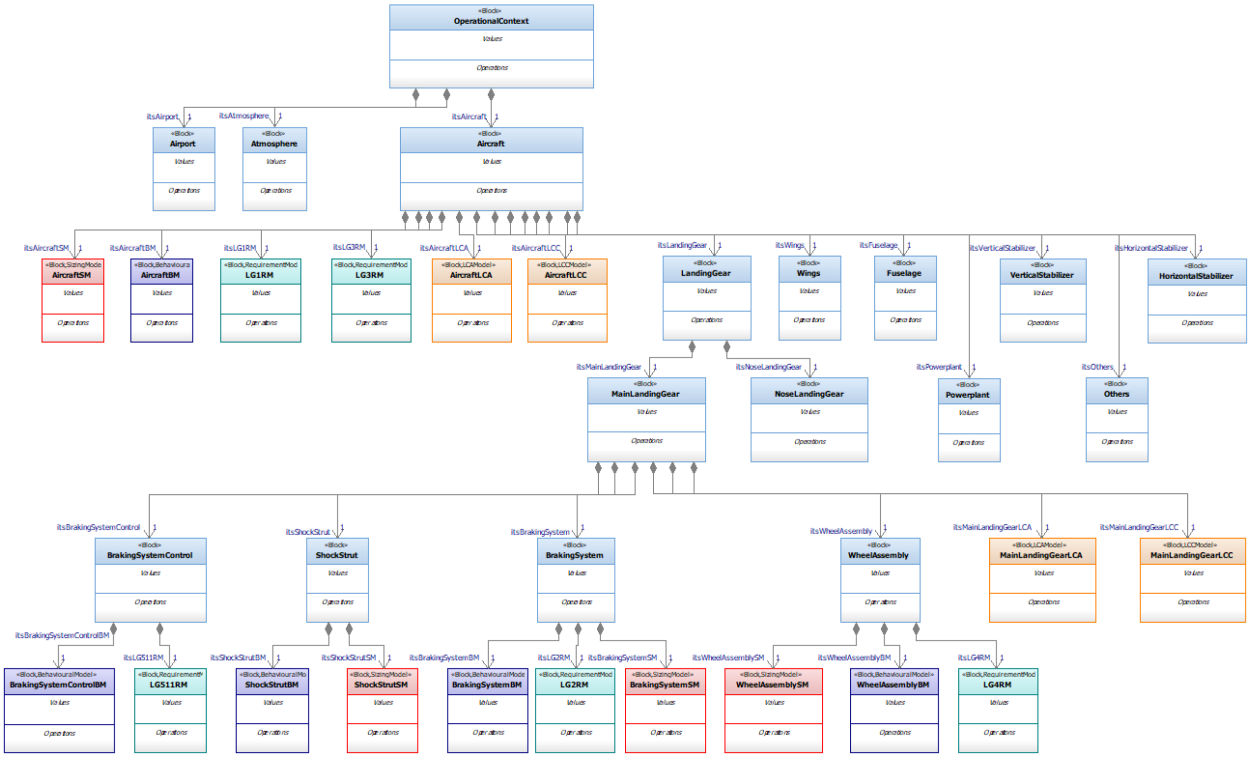

Figure 2.3: Block Definition Diagram for the analyzed aircraft

At the top of the hierarchy is the 'OperationalContext', which encompasses the overall environment in which the aircraft operates, connected to elements like 'Airport' and 'Atmosphere'. The central 'Aircraft' block represents the main system of interest, linked to several subsystems critical to the aircraft's structure and function, such as the 'LandingGear', 'Wings', 'Fuselage', 'Powerplant', 'Vertical Stabilizer', 'Horizontal Stabilizer' and 'Accessories'.

The 'LandingGear' block is composed of 'MainLandingGear' and 'NoseLandingGear' and then is further decomposed into specific components, including the 'Braking System', which itself is detailed with a control block ('BrakingSystemControl'), and other components like 'ShockStrut' and 'WheelAssembly'. Within the 'MainLandingGear', there are also the blocks 'MainLandingGear,LCA' and 'MainLandingGear,LCC'. These aspects will be discussed in detail in chapter 3.1 providing an in-depth explanation of the landing gear system. The diagram uses SysML-specific stereotypes like «Block», «Block,BehavioralModel», and «Block,SizingModel» to categorize the types of models and perspectives being represented, indicating a detailed analysis of both the operational behavior and the design dimensions. The color-coding of the blocks (red, blue, green, orange, etc.) likely indicates different types of analyses or modeling viewpoints, such as behavioral analysis, requirement modeling, and life cycle analysis, as indicated by the 'LCA' and 'LCC' in certain blocks.

This hierarchical decomposition systematically breaks down the aircraft into its subsystems and components, allowing for focused analysis on each part, such as the landing gear, its braking system, shock struts, and wheel assemblies. By incorporating different perspectives like behavioral models, sizing models, and requirement models, the diagram ensures a comprehensive understanding of each component's function, performance, and design requirements. The connection between the aircraft and its operational context ensures that all subsystems are designed considering the environment in which they will function, which is crucial for ensuring the aircraft's overall performance and safety.

2.2 LCA: Manufacturing, Use-Operation and EoL Phase

Referring to [22] in Tab. 2.5 for the analysis of Total Climate Change Impacts by Aircraft Type, reported in PKM (Passenger-Kilometers), and to the number of grams of CO2 equivalent for the main Airbus aircraft (Tab. 2.6), it is possible to calculate the emissions of the main phases shown in the previous paragraph, considering the A320 test case. The CO2 equivalent is a metric that standardizes the impact of various greenhouse gases into a common unit (CO2 equivalent) to facilitate comparison and analysis. In this case, the value of grams of CO2 equivalent shown in Tab. 2.6 represents the amount of grams per passenger per kilometer for a single flight.

Aircraft	Manufacturing	Operations	Fuel Production	Inf. Operation	Inf. Construction
A320	3.52%	78.63%	2.07%	3.5%	12.29%
A330	3.75%	82.6%	0.71%	1.2%	12.74%
A380	1.58%	83.79%	0.57%	0.97%	13.1%

Table 2.5: Lifecycle Impact Distribution for different aircraft models.

Aircraft	gCO2eq
A320	182
A330	106
A380	123

Table 2.6: Grams of CO2 equivalent for the main Airbus aircraft families.

After evaluating the emissions during the manufacturing phase, the use phase considers the model provided by [23], where the climate impact is analyzed as a function of flight distance. In this model, the CO2 equivalent factors for non-CO2 effects, such as NOx, CiC, and H2O, are expressed as functions of flight distances. These equations allow the conversion of emissions from substances other than CO2 into their equivalent CO2 emissions. The equations used are:

$$\mathrm{eqCO}_2^{\mathrm{CO}_2} = 1.0 \tag{2.1}$$

$$\mathrm{eqCO}_2^{\mathrm{NO}_x} = 2.3 \cdot \arctan(3.1D) - 2.0 \tag{2.2}$$

$$\mathrm{eqCO}_2^{\mathrm{CiC}} = 1.1 \cdot \arctan(0.5D) \tag{2.3}$$

$$\mathrm{eqCO}_2^{\mathrm{H}_2O} = 0.2 \cdot \arctan(D) \tag{2.4}$$

$$\mathrm{eqCO}_2^{tot} = \mathrm{eqCO}_2^{\mathrm{NO}_x} + \mathrm{eqCO}_2^{\mathrm{CiC}} + \mathrm{eqCO}_2^{\mathrm{H}_2O} + \mathrm{eqCO}_2^{\mathrm{CO}_2} \tag{2.5}$$

These equations represent the equivalent CO2 factors, where D is the flight distance in 1000 km, for the respective non-CO2 effects, taking into account their influence on the overall climate impact.

After obtaining the emission values for the various main phases (Tab. 2.5), the grams of CO2 equivalent (Tab 2.6) and the total number of CO2 emissions (Eq. 2.5), it is necessary to determine the values related to the Maximum Landing Weight (MLW) of the aircraft under analysis and the expected lifetime (LT) during the preliminary design phase.

Now, MLW represents the highest allowable gross weight for an aircraft during landing. It encompasses the aircraft's empty weight, payload (carrying capacity) and the fuel required for landing. Before determining the fuel consumption per mile in the cruise phase, it is important to assess whether the maximum landing weight can be used as a proxy for operating weight [24]. By considering f as the ratio of empty weight to maximum landing weight (in 1000 lb), a regression of f against MLW gives the following equation:

$$f = 0.59 + 0.00020 \cdot \frac{MLW}{1000} \tag{2.6}$$

In this case study, the MLW for a medium-sized cargo aircraft is estimated at 188,263 lb. Using the equation below, the fuel consumption per mile is determined to be 3.46 gallons/mile. F^* represents a regression model that estimates fuel consumption per mile based on flight characteristics. Specifically, the value of fuel consumption per mile is converted to 8.15 liters per kilometer to ensure consistency with other calculations. Given a single flight distance d of 8046 km, the number of flights per year n set at 350, and a lifetime (LT) of 25 years, the total use-phase fuel consumption $F_{use\_aircraft}$ is computed as follows:

$$F_{use\_aircraft} = F^* \cdot d \cdot n \cdot LT \tag{2.7}$$

The fuel consumption for the generic component, $F_{use\_component}$, is considered to be proportional to the weight fraction of the generic component and is calculated as:

$$F_{use\_component} = F_{use\_aircraft} \cdot \frac{w_{component}}{MLW} \tag{2.8}$$

where $w_{component}$ refers to the generic component's weight. This equation is then employed to determine the use-phase fuel consumption for the 7 main components reported in Tab 2.2.

Before describing the Block Definition Diagrams (BDD) and Internal Block Diagrams (IBD) for LCA, it is important to underline that the blocks used in both diagrams are identical. The key distinction lies in their representation and purpose. The BDD (Block Definition Diagram) provides a hierarchical view of the system, showing the relationships between blocks at different levels, such as between the LCAmodel and the main block. In contrast, the IBD (Internal Block Diagram) focuses on the blocks within the same system level, specifying the interactions and relationships among these components.

In other words, the BDD offers a structural perspective, representing how different system components are organized and related hierarchically. The IBD, on the other hand, provides a more detailed view of how the blocks communicate and interact within the same hierarchical level, emphasizing the internal relationships among the subsystems.

Fig. 2.4 represents another Block Definition Diagram focused on the Life Cycle Assessment (LCA) modeling of an aircraft, specifically detailing the processes related to emissions and weights calculations. At the top, the central block labeled 'AircraftLCA' is defined as '«Block,LCA Model»', indicating that it encapsulates the operations and values relevant to the life cycle assessment of the aircraft. Below this main block, several subordinate blocks are connected, each representing a specific function or operation within the LCA model.

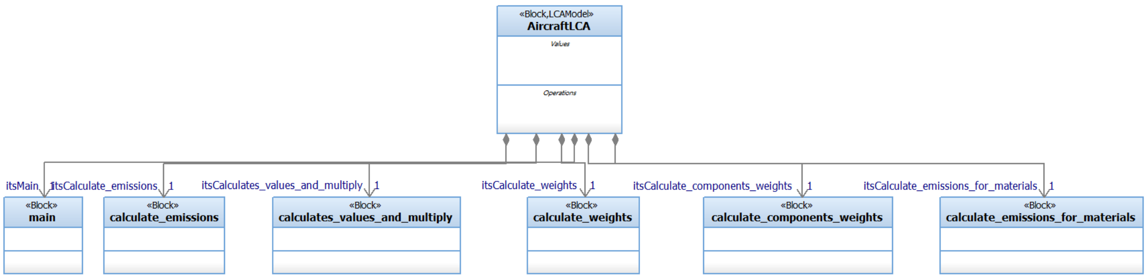

Figure 2.4: Block Definition Diagram for LCA of the aircraft.

Starting from the left, the `main` block appears to serve as the central process that likely coordinates and initiates the LCA calculations. Connected to this is the `calculate_emissions` block, which suggests it handles the calculation of emissions, aggregating data from other operations.

Adjacent to this is the `calculates_values_and_multiply` block, indicating a function that performs calculations involving values and their multiplication, essential for deriving the final emissions of the aircraft and its components.

The diagram further includes the `calculate_weights` block, dedicated to determining the overall weight of the aircraft's components, an important factor in LCA for assessing material usage and related environmental impacts. This process is complemented by the `calculate_components_weights` block, which breaks down the weight calculations to a more detailed level, focusing on individual components rather than the aircraft as a whole.

Finally, on the far right, the `calculate_emissions_for_materials` block is connected, implying a specific operation focused on determining the emissions related to the materials used in the aircraft's construction. This block interacts with the weight calculations to estimate the environmental impact of each material based on its weight and emission factors.

More in detail, Fig. 2.5 illustrates the relationships and data flow between various functions and components involved in calculating emissions and weights within the aircraft Life Cycle Assessment model. These functions have been implemented through Python scripts, and the diagram is divided into several blocks, each representing a specific process or calculation. Each block highlights the input parameters, generated outputs, and the connections between functions, emphasizing the flow of data across different parts of the model.

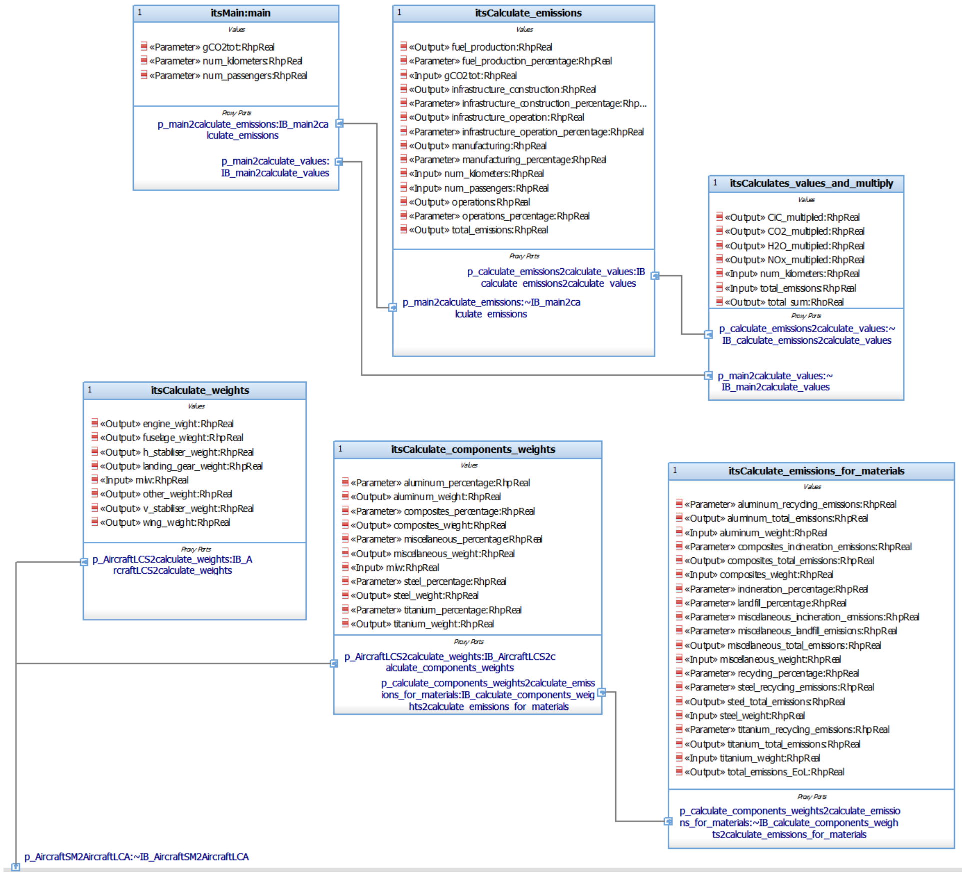

Figure 2.5: Internal Block Diagram for LCA analysis.

The central block, labeled `itsMain:main`, serves as the main entry point for the calculation process, taking inputs such as `gCO2tot`, `num_kilometers`, and `num_passengers` to calculate emissions. This block connects to the `itsCalculate_emissions` block, which details the specific parameters for calculating emissions across various stages, including manufacturing, operations, fuel production, and infrastructure.

Another connected block, `itsCalculates_values_and_multiply`, uses the outputs from `itsCalculate_emissions` to compute the multiplied emissions values for different components like CO2, NOx, CiC, and H2O. Additional blocks, such as `itsCalculate_weights` and `itsCalculate_components_weights`, compute the wei- ghts of various aircraft parts, including engines, fuselage, landing gear, wings etc., as well as the specific material compositions and their associated emissions for end-of-life scenarios.

The `itsCalculate_emissions_for_materials` block focuses on calculating emissions associated with materials during recycling, incineration, and landfill processes. The diagram uses lines with arrows to represent data flow and dependencies between the blocks, indicating a sequential and interconnected structure for conducting a comprehensive life cycle assessment (LCA) of an aircraft, focusing on both emissions and material weights throughout the lifecycle.

The Tab. 2.7 summarizes the input data (in green) to be inserted into the initial calculation setup, yielding as output (in blue) the mass quantity (expressed in lbs) of each component present in Tab 2.2, thereby allowing the calculation of (2.8) for each main aircraft component. This makes it possible, after calculating the total aircraft emissions $eqCO_2^{tot}$ in (2.5), to perform a more detailed analysis of the emission impact of each component during the use operation phase.

Total gCO2-Eq	182
Number of passengers	180
Number of kilometers of one flight	8046
MLW [lb]	188,263
Conversion in kg/lb	0.453592
MLW [kg]	85,395
$\mathbf{w_{LG}}$ **[lb]**	7,530
$\mathbf{w_{WING}}$ **[lb]**	50,831
$\mathbf{w_{ENGINE}}$ **[lb]**	37,653
$\mathbf{w_{FUSELAGE}}$ **[lb]**	35,770
$\mathbf{w_{HSTABILIZER}}$ **[lb]**	20,709
$\mathbf{w_{VSTABILIZER}}$ **[lb]**	11,296
$\mathbf{w_{OTHER}}$ **[lb]**	24,474

Table 2.7: Mass distribution of aircraft components.

The results of the analysis using Python-based software are reported in Tab. 2.8

The first dataset in Fig. 2.6 highlights the CO2 emissions contributions from each major aircraft component.

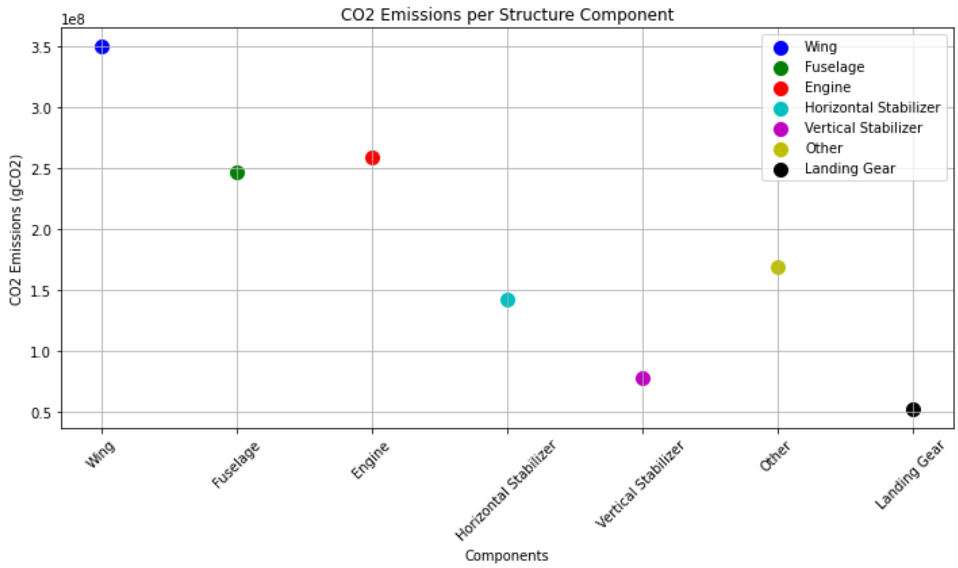

Figure 2.6: CO2 emissions per structure component.

From this breakdown, it's clear that the wing and engine contribute the most significant amounts of CO2 emissions, likely due to their size and the intensive materials used in their construction. The landing gear has the lowest impact, reflecting its relatively smaller mass and simpler design compared to other major components.

The second chart in Fig. 2.7 summarizes the emissions across various phases of the aircraft's lifecycle.

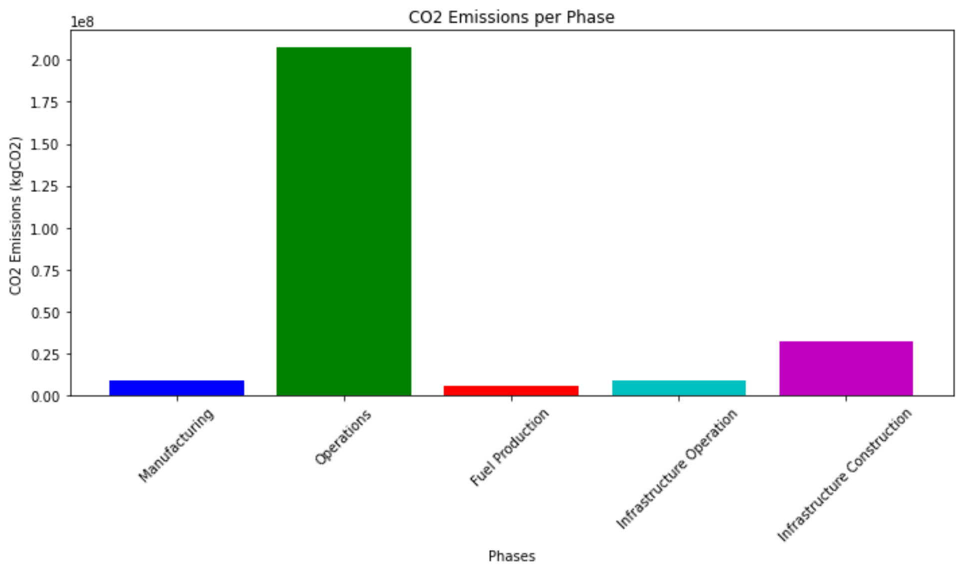

Figure 2.7: CO2 emissions per phase.

Operations dominate lifecycle emissions, accounting for nearly 79% of the total, primarily driven by fuel consumption and flight operations. Manufacturing and infrastructure construction also contribute significantly, but to a much lesser degree. This suggests that efforts to reduce the environmental footprint of aircraft should focus on improving operational efficiency and fuel usage.

The third chart in Fig. 2.8, breaks down the emissions based on the materials used in the aircraft.

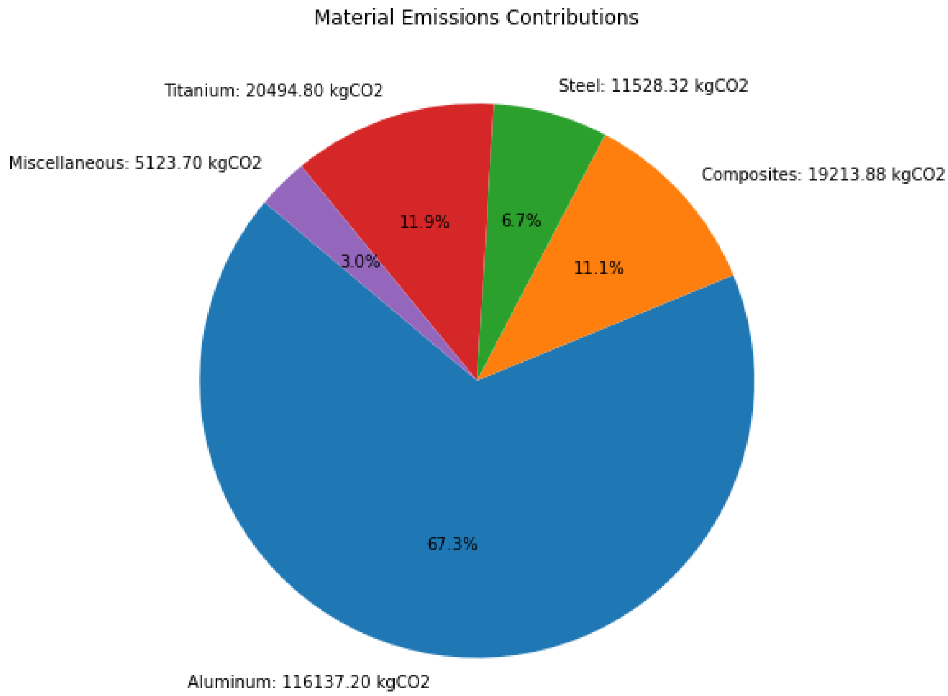

Figure 2.8: Aircraft emissions based on material usage.

Aluminum is responsible for the largest share of material-based emissions, reflecting its extensive use across many aircraft components. Composites also have a notable contribution, emphasizing the environmental considerations of these lightweight but energy-intensive materials. Steel and titanium also contribute to material emissions due to their high embodied energy.

The final chart in Fig. 2.9 illustrates the multiplied CO2-equivalent emissions for key pollutants.

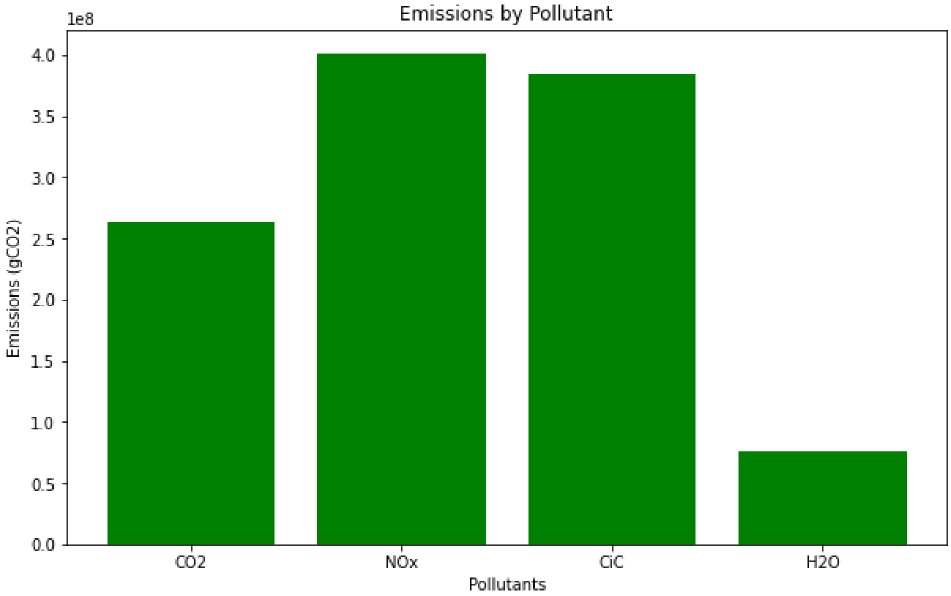

Figure 2.9: Emissions by pollutant.

The most striking observation is that while CO2 emissions are substantial, the combined impact of NOx and CiC is even more significant, highlighting the importance of addressing other greenhouse gases and climate impact factors beyond just carbon dioxide. The relatively lower contribution from H2O indicates its lesser but still notable role in overall environmental impact.

These results underscore the need for a multi-faceted approach in reducing aviation emissions. While operational efficiency is key, addressing the material choices, manufacturing processes, and the broader lifecycle impacts of aircraft components can lead to significant environmental gains. The data further suggests that mitigating the effects of pollutants beyond CO2, such as NOx and CiC, will be crucial in tackling the full spectrum of aviation-related emissions.

Category	Details
Emissions from Each Phase	
Manufacturing	9,278.26 tonCO2
Operations	207,258.43 tonCO2
Fuel Production	5,456.25 tonCO2
Infrastructure Operation	9,225.54 tonCO2
Infrastructure Construction	32,394.84 tonCO2
Total Emissions from Phases	**263,613.32 tonCO2**
The Multiplied Values	
CO2	263,613.32 tonCO2
NOx	400,868.65 tonCO2
CiC	384,843.72 tonCO2
H2O	76,297,34 tonCO2
Total Sum	**1,125,623.03 tonCO2**
Total Emissions for the Aircraft	
Total Aircraft Emissions (excluding EoL)	**1,125,623.03 tonCO2**
Contributions of Each Structure to Total Emissions	
Wing	350,492.65 tonCO2
Fuselage	246,64.98 tonCO2
Engine	259,624.19 tonCO2
Horizontal Stabilizer	142,793.30 tonCO2
Vertical Stabilizer	77,887.26 tonCO2
Other Components	168,755.72 tonCO2
Landing Gear	51,924.84 tonCO2
Calculated Material Weights	
Aluminum	58,068.60 kg
Composites	12,809.25 kg
Steel	7,685.55 kg
Titanium	5,123.70 kg
Miscellaneous	1,707.90 kg
Emissions for Each Material	
Aluminum	116,137.20 kgCO2
Composites	19,213.88 kgCO2
Steel	11,528.32 kgCO2
Titanium	20,494.80 kgCO2
Miscellaneous	5,123.70 kgCO2

Table 2.8: Results of the emissions for the aircraft LCA model.

The table provides a breakdown of emissions for each phase of the lifecycle in tonCO2, including manufacturing, operations, fuel production, and infrastructure. The results also include multiplied values for different pollutants (CO2, NOx, CiC, and H2O), as well as the total emissions excluding the end-of-life (EoL) phase. Additionally, the contribution of different aircraft structures, such as the wing, fuselage, and engine, to the total emissions is detailed. Material weights and the corresponding emissions for aluminum, composites, steel, titanium, and miscellaneous materials are reported separately in kgCO2.

For the EOL analysis, three disposal solutions have been considered for the main materials that constitute the entire aircraft structure: recycling, landfill and incineration. Based on the results shown in Tab. 2.8 and by creating Tab. 2.9, emissions for the end-of-life phase of the aircraft were calculated. For materials such as Aluminum, Steel, and Titanium, a complete recycling process was assumed, while for composites, full incineration was considered. For miscellaneous materials, a 50% landfill and 50% incineration approach was adopted.

	Aluminum	**Composites**	**Steel**	**Titanium**	**Miscellaneous**
Recycling (%)	100%	0%	100%	100%	0%
Landfilling (%)	0%	0%	0%	0%	50%
Incineration (%)	0%	100%	0%	0%	50%
Emissions for Recycling [kg CO2/kg]	2	0	1.5	4	0
Emissions for Landfilling [kg CO2/kg]	0	0	0	0	5
Emissions for Incineration [kg CO2/kg]	0	3	0	0	1

Table 2.9: Analysis of Recycling, Landfilling, and Incineration for different structural materials.

It is important to note that data used in the previous table are based on personal estimates made during the calculation phase and therefore provide only an approximate indication.

For calculating the total emissions during the EoL phase, it is sufficient to perform equations (2.9) and (2.10), where i stands for the generic material present in the previous table:

$$emissions_i = weight_i \cdot disposal_emissions_i \tag{2.9}$$

In this equation, $emissions_i$ represents the total emissions produced by the disposal of a given material i. The term $weight_i$ refers to the weight of the material being disposed of, and $disposal\_emissions_i$ indicates the emissions per unit weight (kg CO2 per kg) associated with the specific disposal method (e.g., recycling, landfilling, or incineration) for that material.

Thus, $disposal\_emissions_i$ quantifies how much CO2 is released per kilogram of the material during its end-of-life processing, depending on how it is treated.

The total emissions for EoL phase are calculated by summing the emissions from all the individual materials used in the system, as follows:

$$total\ emissions\ for\ EoL = \sum_i emissions_i \tag{2.10}$$

This way, it is possible to obtain the total emissions of the aircraft over its entire life cycle, as resumed in Tab. 2.10.

Description	**[tonCO2]**
Total EoL emissions	172,497.900
Total aircraft emissions (excluding EoL)	1,125,623.03
Total aircraft emissions including EoL	**1,298,120.93**

Table 2.10: Emissions from End of Life phase and total aircraft emissions.

2.3 LCC: Use-Operation and EoL Analysis

In this section, the Life Cycle Cost (LCC) analysis of the A320 excludes the costs associated with the manufacturing phase. This decision is due to the complexity of the production process, which involves a vast number of components and various types of processes specific to each main part of the aircraft. Additionally, the limited availability of data from manufacturers has made it difficult to accurately assess the manufacturing phase. Therefore, this analysis focuses exclusively on the Use Operation and End of Life phases.

Conversely, in the detailed analysis of the landing gear presented in chapter 3.1, a comprehensive assessment of the entire life cycle will be carried out.

Fig.2.10 is a block definition diagram illustrating the structure and relationships within the `AircraftLCC` (Life Cycle Cost) model. The central block, labeled `AircraftLCC`, represents the main entity of the model. This block does not explicitly show any values or operations, indicating that it serves as a high-level aggregation of the processes related to aircraft life cycle costing.

There are three primary blocks connected to `AircraftLCC`: `calculate_eol_costs`, `calculate_fuel_consumption`, and `main`. Each of these blocks is connected to `AircraftLCC` via association lines labeled `itsCalculate_eol_costs`, then there's `itsCalculate_fuel_consumption` block and `itsMain`, respectively. `AircraftLCC` utilizes these blocks to perform specific calculations, using lines with arrows to indicate directional associations between the main block and its components and demonstrating a modular approach to modeling the life cycle costs of an aircraft.

The `calculate_eol_costs` block is designated for computing the end-of-life costs associated with the aircraft. Similarly, the `calculate_fuel_consumption` block focuses on determining the fuel consumption throughout the aircraft's operational life. The `main` block serves as the orchestrator for initiating the calculations, representing the primary workflow of the cost model.

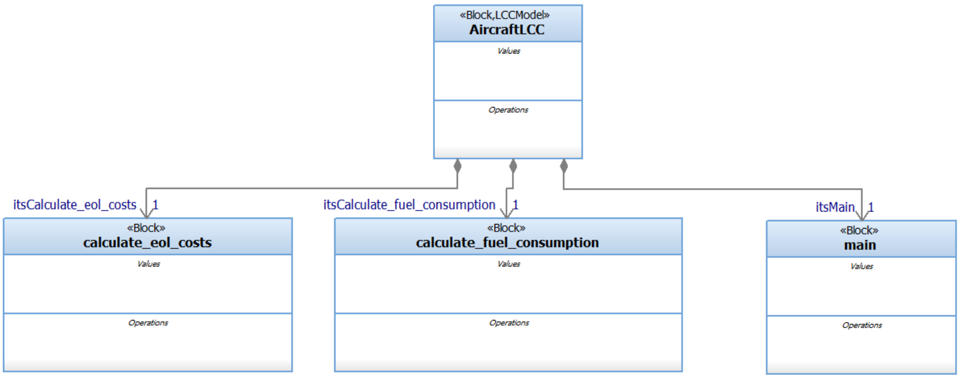

Figure 2.10: Block Definition Diagram for LCC of the aircraft

The Fig. 2.11 depicts in detail the relationships and data flow between different components of an aircraft life cycle cost model. The central block, labeled `itsMain`, contains multiple input and output parameters related to various aspects of aircraft operation and cost calculation. These parameters include percentages for all aircraft components, operational parameters (`distance_per_flight`, `num_flights_per_year`, `lifetime`), and financial factors (`fuel_price_per_liter`).

`ItsMain` block is connected to two other blocks: `itsCalculate_fuel_consumption` and `itsCalculate_eol_costs`. The `itsCalculate_fuel_consumption` block is responsible for calculating the fuel consumption for various aircraft components. It takes similar input parameters as the `itsMain` block and provides outputs for the fuel consumption of each component, indicating a detailed breakdown of fuel usage across different parts of the aircraft.

The `itsCalculate_eol_costs` block calculates the EOL costs for the aircraft components. It uses inputs like `cost_recycling`, `cost_incineration`, and finally `cost_landfill` along with component-specific parameters to determine the EOL costs. The outputs of this block include the calculated EOL costs for each component, providing insights into the financial impact of disposing of or recycling the aircraft at the end of its operational life.

The diagram uses connecting lines to show how the `itsMain` block interfaces with the `itsCalculate_fuel_consumption` and `itsCalculate_eol_costs` blocks, with labeled proxy ports (such as `p_main2calculate_fuel_consumption` and the associated one for the EoL, `p_main2calculate_eol_costs`) indicating the pathways for data flow and functional integration. These connections represent a comprehensive approach to modeling the life cycle cost of an aircraft, from operational fuel consumption to end-of-life disposal costs.

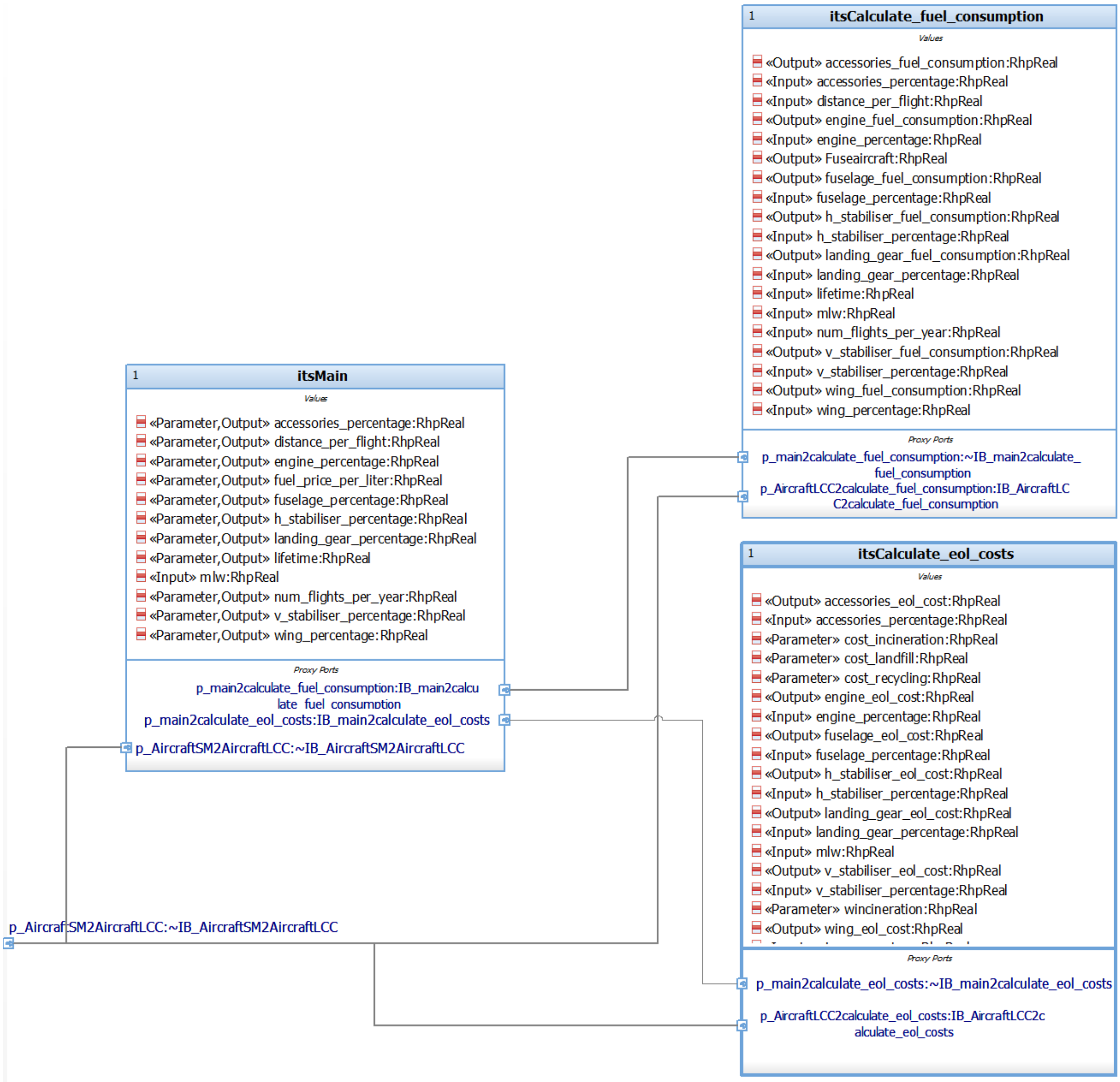

Figure 2.11: Internal Block Diagram for LCC analysis

So, using the data provided in Tab. 2.2 and Eqs. (2.7) and (2.8), it is first possible to quantify the fuel consumption for each component over the aircraft's lifetime. Subsequently, the costs associated with each primary structure of the aircraft during the use phase can be calculated using Eq. (2.11), considering in this analysis the *kerosene fuel price* equal to 0.224 EUR/l, and applying (2.12) the total use phase cost is obtained. The final results are presented in Tab. 2.11.

$$use\ phase\ cost_{structure_i} = fuel\ consumption_{structure_i} \cdot kerosene\ fuel\ price \quad (2.11)$$

$$Total\ Use\ Phase\ Cost = \sum_i use\ phase\ cost_{structure_i} \quad (2.12)$$

Fig. 2.12 shows that the wings and engines are the components with the highest fuel consumption and usage costs, reflecting their importance and complexity. This

Component	Fuel Consumption (liters)	Use Phase Costs (€)
Landing Gear	22,951,633.39	5,141,165.88
Wing	154,923,525.37	34,702,869.68
Fuselage	109,020,258.59	24,420,537.92
Vertical Stabilizer	34,427,450.08	7,711,748.82
Horizontal Stabilizer	63,116,991.82	14,138,206.17
Engine	114,758,166.94	25,705,829.39
Accessories	74,592,808.51	16,708,789.11
Total	**574,790,834.70**	**128,529,146.97**

Table 2.11: Fuel consumption and use phase costs for each component over the aircraft's lifetime.

is due to their weight significantly impacting the aircraft's structure. The fuselage and accessories have intermediate costs and consumption, while the landing gear and stabilizers have the lowest impact in terms of both fuel consumption and usage costs.

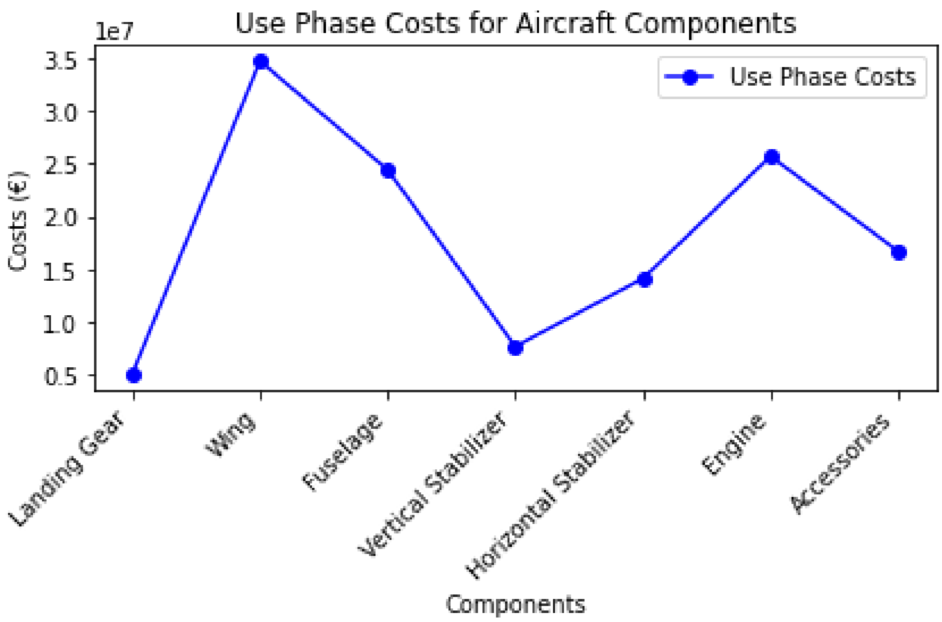

Figure 2.12: Use phase cost for aircraft components.

Fuel consumption accounts for a significant portion of an airliner's operating costs. These costs can be lowered by developing more efficient engines, reducing aerodynamic drag, optimizing the aircraft's flight path, or by decreasing its weight. The desire to reduce weight was the primary reason for transitioning from metals to composite materials, and the percentage of composites in the total structural weight continues to rise, as shown in Fig. 2.13.

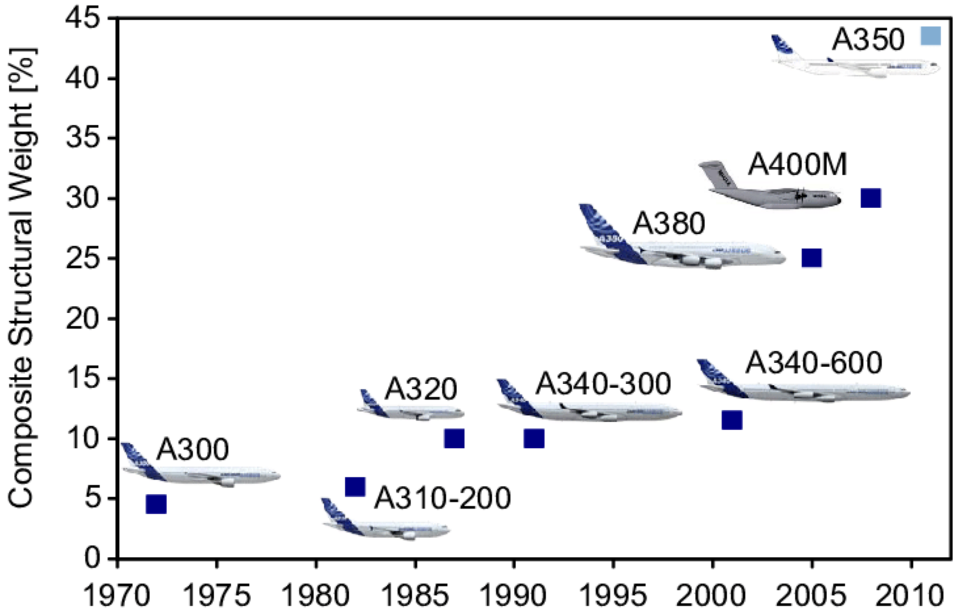

Figure 2.13: Portion of composite materials in Airbus aircraft.
(courtesy of H. Assler, Airbus Deutschland GmbH)

The data presented in Tab. 2.12 summarize the analysis of costs and material distribution at the End-of-Life (EoL) phase for various aircraft components. The table includes:

1. **Component weights**: It outlines the total weight of each part, such as the landing gear, wings, fuselage, stabilizers, engines, and accessories.

2. **Material distribution at End-of-Life**: - Recycling: The percentage of each component's weight allocated for recycling (ranging from 50% to 65%). - Landfill: The percentage sent to landfill (ranging from 30% to 35%). - Incineration: The percentage assigned to incineration (ranging from 5% to 20%).

3. **Associated costs**: - Recycling Cost: The cost (or benefit) of recycling (with values ranging from -0.75 €/kg to -2.25 €/kg, indicating a potential economic gain). - Landfill Cost: The cost of sending materials to landfill (approximately 8 €/kg). - Incineration Cost: The cost for incinerating materials (around 0.2 €/kg to 1 €/kg).

These percentages and costs are personal estimates used for calculations due to the limited availability of precise industry data. The scarcity of data can be attributed to the proprietary nature of such information, varying recycling technologies, and inconsistent practices across different manufacturers. This analysis aims to provide a rough estimate of EoL costs to support decision-making despite the inherent data limitations.

Applying equation (2.13), the end-of-life cost for each aircraft structure component

	Mass fractions [kg]				Costs [€]		
Component	**Weight**	**Recycling**	**Landfill**	**Incineration**	**Recycling**	**Landfill**	**Incineration**
Landing Gear	w_{LG}	$0.50w_{\mathrm{LG}}$	$0.30w_{\mathrm{LG}}$	$0.20w_{\mathrm{LG}}$	-0.75	0.2	1
Wing	w_{Wing}	$0.60w_{\mathrm{Wing}}$	$0.35w_{\mathrm{Wing}}$	$0.05w_{\mathrm{Wing}}$	-1.50	8	0.2
Fuselage	w_{Fuselage}	$0.65w_{\mathrm{Fuselage}}$	$0.30w_{\mathrm{Fuselage}}$	$0.05w_{\mathrm{Fuselage}}$	-2.25	8	0.2
Horizontal Stabilizer	w_{HS}	$0.65w_{\mathrm{HS}}$	$0.30w_{\mathrm{HS}}$	$0.05w_{\mathrm{HS}}$	-1.50	8	0.2
Vertical Stabilizer	w_{VS}	$0.65w_{\mathrm{VS}}$	$0.30w_{\mathrm{VS}}$	$0.05w_{\mathrm{VS}}$	-1.50	8	0.2
Engine	w_{Engine}	$0.60w_{\mathrm{Engine}}$	$0.30w_{\mathrm{Engine}}$	$0.10w_{\mathrm{Engine}}$	-2.25	8	0.2
Accessories	w_{Acc}	$0.65w_{\mathrm{Acc}}$	$0.30w_{\mathrm{Acc}}$	$0.05w_{\mathrm{Acc}}$	-1.50	8	0.2

Table 2.12: End-of-Life (EoL) data for each component, including weights and costs.

is calculated as follows:

$$EoL\_Cost_{structure_i} = w_{recycling} \cdot cost_{recycling} + w_{landfill} \cdot cost_{landfill} + w_{incineration} \cdot cost_{incineration} \tag{2.13}$$

Moreover, by summing the EoL costs of all components i as in Eq. (2.14), the total end-of-life cost is obtained:

$$Total\ EoL\ Cost = \sum_i EoL\_Cost_{structure_i} \tag{2.14}$$

Finally, the overall aircraft lifecycle cost is determined by adding the total use phase costs and the total end-of-life costs applying (2.15):

$$Total\ Aircraft\ Cost = Total\ Use\ Phase\ Cost + Total\ EoL\ Cost \tag{2.15}$$

In Fig. 2.14 and in the Tab. 2.13 the results indicate that all components incur significant costs, except for the landing gear that stands out with a net savings of €-392.82, suggesting a potential revenue from recycling rather than a cost.

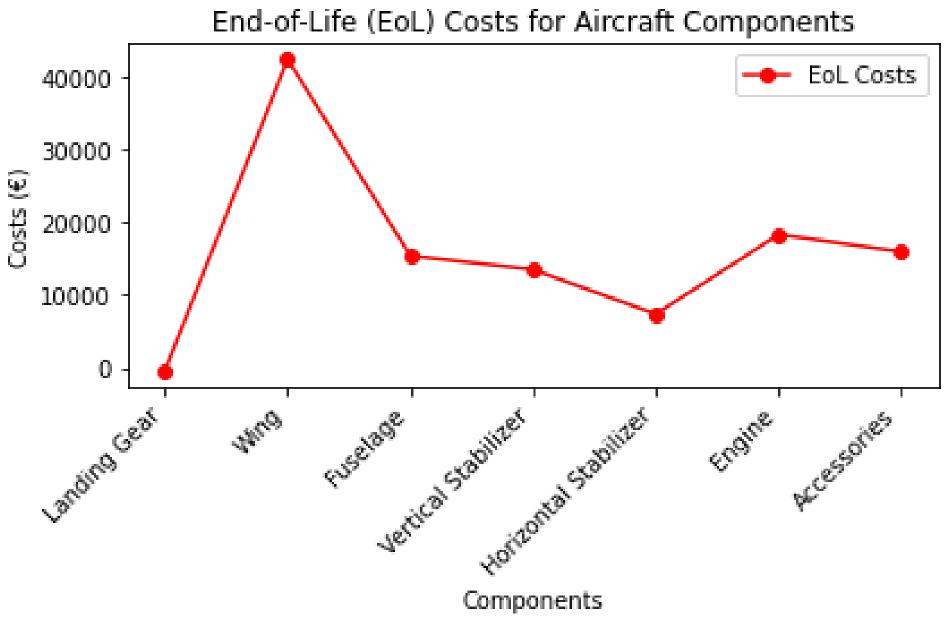

Figure 2.14: EoL Costs for Aircraft Components.

In comparison, the Use Phase costs, which encompass the fuel consumption over the aircraft's operational life, are considerably higher. For instance, wing's use phase cost is particularly substantial at €34,702,869.68, overshadowing its EoL cost by over 800 times. Similarly, all the other components demonstrate that their operational fuel costs are significantly higher than their end-of-life costs.

Component	**EoL Costs (€)**
Landing Gear	-392.82
Wing	42,308.75
Fuselage	15,373.16
Horizontal Stabilizer	13,479.54
Vertical Stabilizer	7,352.47
Engine	18,274.44
Accessories	15,930.36
Total Aircraft Cost	**128,641,472.88**

Table 2.13: End-of-Life (EoL) costs for each component and total aircraft cost.

Chapter 3

Use case 2: The Landing Gear

3.1 Overview of Aircraft Landing Gear: Functionality, Design and System Integration

Aircraft landing gears play a crucial role in supporting the aircraft during various ground operations, such as take-off, landing impact, taxiing and towing [25]. Designed to minimize mass and maintain ground clearance, landing gears are typically slender structures that respond dynamically to ground load excitations. Since the landing gear is one of the few systems on the aircraft without redundancies, understanding its dynamics is vital for both aircraft design and safety [26].

It generally includes a nose gear with steering capabilities, along with two main landing gears equipped with retraction actuators, bracing, retraction mechanisms, wheels, tires, and brakes. This equipment is expensive and occupies both space and weight during flight, yet it does not contribute to the aircraft's performance in the air; thus, it can be considered a parasitic element during flight. Despite this, the landing gear remains essential for take-off and landing, as no alternative landing system has yet proven to be as effective.

The landing gear system is fundamental to aircraft performance and must meet several complex, and sometimes conflicting, requirements. During landing, it must absorb vertical energy through shock absorbers and horizontal kinetic energy through brakes. While taxiing, it must support the aircraft over taxiways and runways of varying conditions.

The landing gear and its associated systems present a significant design challenge: it is a system, structure, and machine all in one. It must support the aircraft on the ground, absorb landing and braking forces, facilitate maneuvering, and retract to reduce drag. Since it is not needed during flight, minimizing its weight is critical.

It is among the most intricate and varied systems on an aircraft. Experts in landing gear design must have knowledge across multiple engineering disciplines, including materials science, mechanisms, structural engineering, heat transfer, aerodynamics, and tribology. Depending on the aircraft's requirements, a landing system might be as simple as wheels and tires attached to the aircraft structure or as complex as a system designed for operations on unpaved runways, including steering, kneeling, and retracting capabilities.

The landing gear system performs several key functions [27]:
1. It supports the aircraft on the ground with its wheels and tires;
2. the tires and shock absorbers absorb vertical energy during landing and reduce shocks during ground maneuvering;
3. the brakes manage forward energy and keep the aircraft stationary when stopped or parked;
4. differential braking and steering enable the aircraft to turn and maneuver on the ground.

3.2 LCA of The Landing Gear

The diagram in Fig.3.1.presents the structure of LCA and LCC model specifically focused on the landing gear of the analyzed aircraft, referred to as the `MainLandingGearLCALCC` block at the top. It serves as the central controller for operations related to both LCA and LCC calculations. The model breaks down into several sub-components, each handling a distinct part of the analysis.

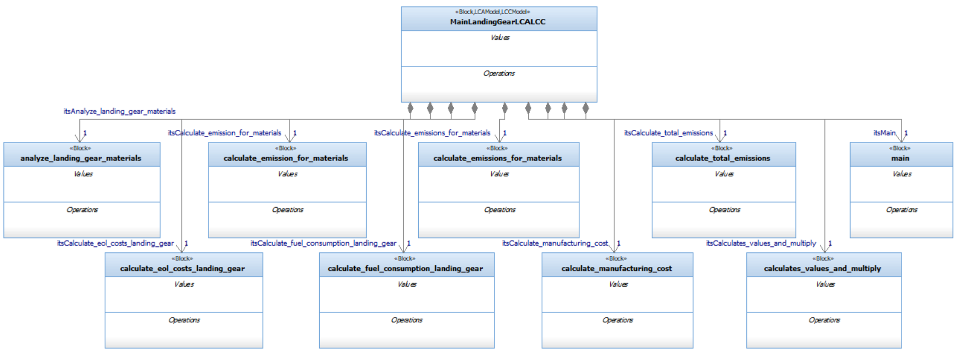

Figure 3.1: Block Definition Diagram for LCA and LCC of the Landing Gear

Starting from the left, the `itsAnalyze_landing_gear_materials` block suggests the analysis of the materials used in the landing gear, crucial for evaluating the environmental impacts and costs associated with material selection.

Directly connected below it is the `calculate_eol_costs_landing_gear` block, indicating a function that calculates the end-of-life costs of the landing gear, a necessary consideration in LCC analysis to account for recycling, incineration or landfilling.

Moving to the right, the `calculate_emission _for_materials` and `calculate _emissions_for_materials` blocks manage emissions associated with the materials used in the landing gear. They handle different aspects of material-related emissions calculations, such as emissions during production or from the materials themselves. These are linked to broader emissions-related processes within the model.

Next, the `calculate_fuel_consumption_landing_gear` block is dedicated to determining the fuel consumption attributed to the landing gear. This is likely associated with its weight and design, as these factors influence fuel efficiency and consumption during the aircraft's operation.

Adjacent to that, the `calculate_manufacturing_cost` block handles the costs associated with manufacturing the landing gear. This would include labor, materials, machine and development expenses, which are crucial for understanding the overall life cycle costs.

The `calculate_total_emissions` block is responsible for aggregating all emissions associated with the landing gear, likely pulling data from the emissions and fuel consumption blocks to provide a total environmental impact figure.

Finally, the `calculates_values_and_multiply` block performs operations that involve value-based calculations and their multiplication, suggesting it helps in deriving final values for both emissions and costs, based on input parameters. This block links to the `main` block on the far right, which serves as the coordinator of these operations, ensuring all processes run correctly and data flows between the necessary components. Together, these interconnected blocks provide a comprehensive framework for assessing both the environmental and economic impacts of the landing gear across its life cycle.

Going more in detail as depicted in Fig. 3.2, `itsMain` block acts as the core of the system, containing various input and output parameters such as distance per flight, fuel price per liter, fuel production percentage, CO2 equivalent, infrastructure and operational percentages, and manufacturing and operational details. `itsMain` is linked to other blocks through labeled proxy ports, which represent the flow of data between different subsystems.

The `itsCalculate_fuel_consumption_landing_gear` block is responsible for calculating fuel consumption, based on inputs like distance per flight, lifetime, and landing gear weight, with outputs that detail the fuel consumption breakdown for the landing gear.

Similarly, the `itsCalculate_eol_costs_landing_gear` block computes EOL costs for the landing gear, taking into account parameters like recycling, incineration, and landfill costs.

The `itsAnalyze_landing_gear_materials` block evaluates the total material weight for the landing gear components. while `itsCalculate_manufacturing_cost` calculates the total manufacturing costs, factoring in base labor and material costs, development costs, machine operation, and overall production costs.

Lastly, the `itsCalculate_emission_for_materials` block estimates the total emissions based on specific emission factors for the materials used in the aircraft.

Each of these blocks interacts with `itsMain` through clearly defined data pathways, creating a comprehensive model for analyzing both the financial and environmental impacts of an aircraft's life cycle.(Fig. 3.2).

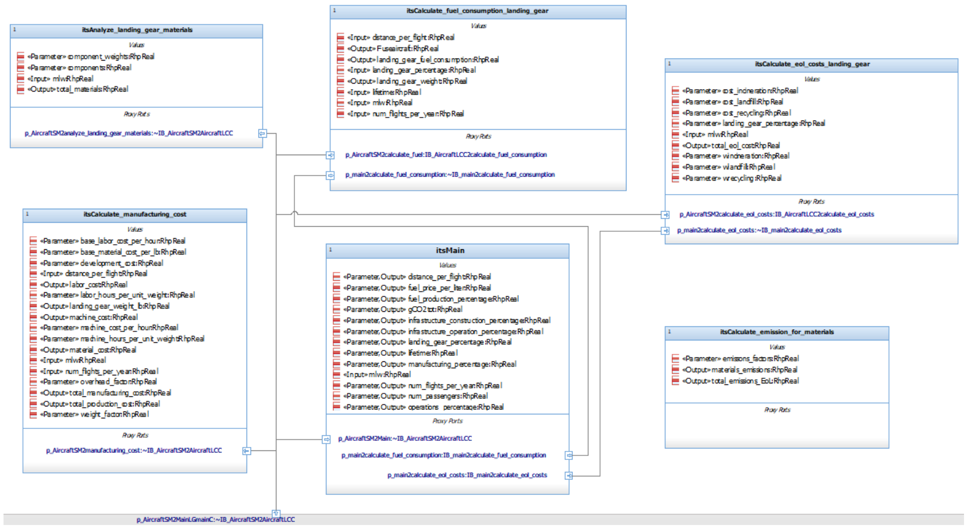

Figure 3.2: Internal Block Diagram for LCA and LCC of the Landing Gear

The LCA analysis for the landing gear has already yielded results for the manufacturing and operational phases, as discussed in the previous chapter. Consequently, the following Tab. 3.1 summarizes the results previously obtained.

Parameter	**Value**
Landing Gear Fuel Consumption	22,951,633.39 liters
Manufacturing and Use Operation Emissions	45,020.419 tonCO_2
Landing Gear Weight (w_{LG})	4%$w_{aircraft}$

Table 3.1: Landing Gear Fuel Consumption, Emissions, and Weight.

Regarding the end-of-life analysis of the landing gear, a more detailed study is conducted on the composition of materials and the key components involved. Although this analysis is a simplified representation of the landing gear's material composition, it still provides a reasonable estimate of the end-of-life emissions. While the study lacks comprehensive detail, it effectively offers a preliminary understanding of the environmental impact associated with the disposal phase, helping to quantify potential emissions during this final stage.

The landing gear analyzed consists of three primary components:

- **Main Struts**: 50% of w_{LG}
- **Brake Systems**: 30% of w_{LG}
- **Wheels**: 20% of w_{LG}

The materials used in its construction include :

- Aluminum
- Carbon Composites
- High-Strength Steel
- Titanium
- Stainless Steel

The Tab. 3.2 details the percentage composition of these materials within each of the landing gear's three main structures, along with their associated emission factors (Tab. 3.3). The breakdown offers valuable insights into the environmental impact of each material type, which is crucial for assessing the overall emissions during the end-of-life phase.

Component	**Material**	**Proportion**	**Mass (kg)**
Main Struts	Titanium	70%	1,707.89
	Aluminum	20%	
	High Strength Steel	10%	
Brake Systems	Carbon Composites	60%	1,024.74
	Stainless Steel	30%	
	Aluminum	10%	
Wheels	Aluminum	80%	683.16
	High Strength Steel	10%	
	Carbon Composites	10%	

Table 3.2: Material Composition and Mass of the Landing Gear Components.

Material	Emissions Factor (kgCO2/kg)
Aluminum	2
Carbon Composites	3
High Strength Steel	1.5
Titanium	4
Stainless Steel	1.5

Table 3.3: Emissions Factors for Materials Used in Landing Gear.

So, the first step is to determine the weight of each material in the landing gear. For each component (like Main Struts, Brake Systems, and Wheels), there is a need to calculate the weight of each material by multiplying the component's total weight by the material's percentage composition.

The weight of a given material in a component is calculated as follows:

$$\text{Weight}_{\text{material}} = \text{Component Weight} \cdot \text{Material Percentage} \tag{3.1}$$

where:

$$\text{Component Weight} = \text{Total Landing Gear Weight} \cdot \text{Component Proportion} \tag{3.2}$$

This allows us to sum the material contributions from all components.

Next, the CO2 emissions associated with each material have to be calculated. This is done by multiplying the weight of the material by its emissions factor. The emissions factor represents the amount of CO2 emitted per kilogram of the material (in kgCO2/kg). The equation for calculating emissions for each material is:

$$\text{Emissions}_{\text{material}} = \text{Weight}_{\text{material}} \cdot \text{Emissions Factor}_{\text{material}} \tag{3.3}$$

The total EoL emissions are obtained by summing the emissions from all materials:

$$\text{Total EoL Emissions} = \sum_{\text{material}} \text{Emissions}_{\text{material}} \tag{3.4}$$

Finally, the overall emissions contribution from the landing gear, including both the use phase and end-of-life, is calculated as:

$$\begin{aligned}\text{Landing Gear Emissions} = {} & \text{Manufacturing and Use Operation Emissions} + \\ & \text{Total EoL Emissions}\end{aligned} \tag{3.5}$$

The obtained results are presented in the Tab. 3.4. In the previous analysis of Chapter 2.2, the Landing Gear Total Emissions were determined to be 51,924.84 tonCO2. In the current analysis, however, the total emissions amount to 54,652.929 tonCO2. This discrepancy can be attributed to several factors. Firstly, the current analysis may have included a more comprehensive breakdown of material emissions, with particular attention given to specific contributions from materials like titanium and carbon composites. Additionally, variations in data sources or emission factors could lead to higher precision but also slight variations in the calculated emissions.

Furthermore, it is important to note that in the previous analysis, the total emissions of 51 million g CO2 encompassed all phases of the aircraft's End of Life (EoL), with the emissions distributed more generally across all structures. In contrast, the current analysis focuses exclusively on the specific emissions associated with the landing gear. This more targeted approach provides a clearer and potentially lower estimation of the emissions specific to the landing gear, which likely contributes to the observed reduction in the total emissions calculated.

Material Emissions for Landing Gear	**CO_2 Emissions (kg)**
Titanium	4,782.10
Aluminium	1,981.15
High Strength Steel	358.66
Carbon Composites	2,049.47
Stainless Steel	461.13
Manufacturing and Use Operation Emissions	**45,020.419 ton CO_2**
Total EoL Emissions	**9,632.510 ton CO_2**
Landing Gear Emissions	**54,652.929 ton CO_2**

Table 3.4: LCA results of the Landing Gear.

Finally, Fig. 3.8 displays a pie chart representing the distribution of End-of-Life emissions by material. The chart highlights how the emissions are predominantly driven by titanium, with other materials having a relatively lower impact.

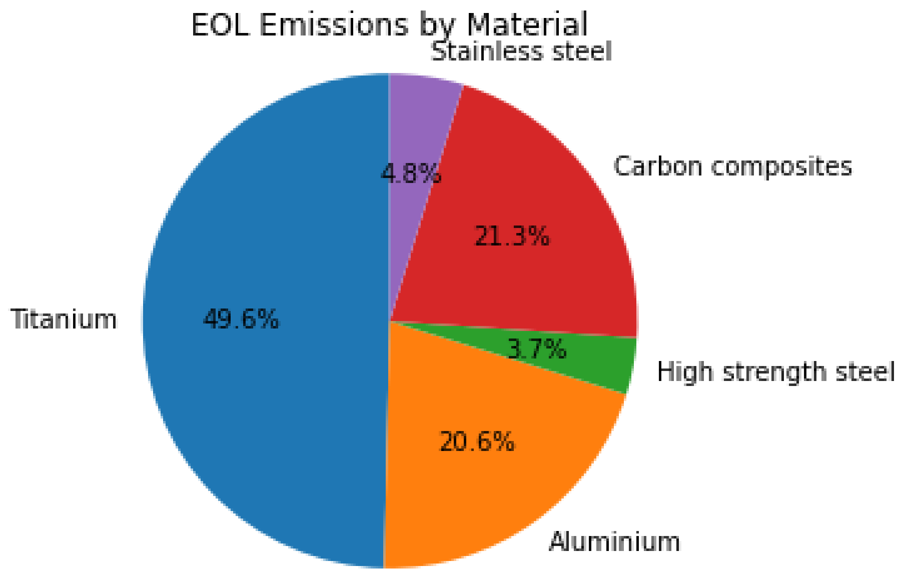

Figure 3.3: EOL Emissions by material of Landing Gear.

3.3 LCC of The Landing Gear

Regarding the analysis of the landing gear, the results for the use-operation phase (Tab. 2.11) and the end-of-life phase (Tab. 2.13) have already been obtained. However, a comprehensive analysis must also include the manufacturing phase, which can significantly impact the overall costs and environmental footprint of the component. For this reason, this section offers a discussion on a potential approach for quantifying the costs associated with the manufacturing phase of the landing gear.

The **overhead cos**t represents the indirect expenses incurred during the production of a product that cannot be directly attributed to a specific product or service. These costs include:

1. *Administrative Costs:* salaries of administrative staff, management, and office expenses.

2. *Utility Costs:* electricity, water, heating, and cooling.

3. *Maintenance Costs:* expenses related to the upkeep of equipment and infrastructure.

4. *Rent:* lease costs for the production facility if it is rented.

5. *Depreciation of equipment:* the reduction in value of equipment over time.

Overhead costs are typically calculated as a percentage of direct or total production costs and are included in the overall cost to determine the final price of the product.

Then, in order to account for variations in operational conditions, the manufacturing costs are adjusted based on the flight distance, frequency of flights, and overhead costs. The adjustments are calculated as follows:

$$\text{distance\_factor} = 1 + \left(\frac{\text{distance\_per\_flight\_km}}{10000}\right) \tag{3.6}$$

$$\text{frequency\_factor} = 1 + \left(\frac{\text{num\_flights\_per\_year}}{1000}\right) \tag{3.7}$$

The **distance factor** adjusts the production cost according to the average flight distance per flight, where the formula indicates that for every 10,000 km of average flight distance, the cost increases by one unit (100%). This adjustment is based on the assumption that longer flight distances may require more durable materials or more robust designs, leading to higher production costs. Similarly, the **frequency factor** adjusts the cost based on the number of flights performed annually. For every additional 1,000 flights, the cost increases by one unit (100%), reflecting the potential need for enhanced materials or production techniques to withstand increased wear and tear on the landing gear.

$$\begin{aligned} \text{total\_manufacturing\_cost} = &\text{total\_production\_cost} \cdot \\ &\text{distance\_factor} \cdot \\ &\text{frequency\_factor} \cdot \text{overhead\_factor} \end{aligned} \tag{3.8}$$

The overall manufacturing cost of the landing gear, *total_ manufacturing_ cost*, is determined by multiplying the initial production cost, *total_production_ cost*, by the distance factor, frequency factor, and overhead factor, as reported in Eq.3.8. This approach ensures that the total production cost realistically reflects the impact of operational conditions and indirect costs, providing a more accurate estimation of the manufacturing phase's contribution to the overall costs of the landing gear system.

The methodology developed to estimate the total production cost of the landing gear involves several key factors, as highlighted by the equations and parameters provided in the Tab. 3.5.

The first equation calculates the estimated weight of the landing gear:

$$\text{landing\_gear\_weight}_{\text{lb}} = \text{mlw}_{\text{lb}} \cdot \text{weight\_factor} \tag{3.9}$$

In this equation, the maximum landing weight (mlw_{lb}) of the aircraft is multiplied by a weight factor, which represents the percentage of the *MLW* attributed to the

Parameter	Value
Base material cost per pound	5.0 Euros per lb
Base labor cost per hour	50.0 Euros per hour
Machine cost per hour	100.0 Euros per hour
Development cost	20000.0 Euros
Overhead factor	1.2 (20% overhead)
Weight factor	0.04 (assumed percentage of MLW for landing gear weight)
Labor hours per unit weight	2.0 hours per lb
Machine hours per unit weight	1.0 hours per lb

Table 3.5: Cost factors and parameters used for production calculation.

landing gear (assumed to be 4%, as indicated in the table). This value gives the estimated weight of the landing gear in pounds. Next, the material cost is calculated as follows:

$$\text{material\_cost} = \text{landing\_gear\_weight}_{\text{lb}} \cdot \text{base\_material\_cost}_{\text{lb}} \tag{3.10}$$

The material cost depends on the estimated weight of the landing gear and the base material cost per pound, listed as 5 Euros per pound in the table. The labor cost is determined using the following equation:

$$\begin{aligned}\text{labor\_cost} =& \text{landing\_gear\_weight}_{\text{lb}} \cdot \\ & \text{labor\_hours}_{\text{unit weight}} \cdot \text{base\_labor\_cost}_{\text{hour}}\end{aligned} \tag{3.11}$$

In this case, the labor cost is based on the number of labor hours required per unit of weight (2 hours per pound) and the base labor cost per hour (50 Euros per hour). The machine cost is estimated with the equation:

$$\begin{aligned}\text{machine\_cost} =& \text{landing\_gear\_weight}_{\text{lb}} \cdot \\ & \text{machine\_hours}_{\text{unit weight}} \cdot \text{machine\_cost}_{\text{hour}}\end{aligned} \tag{3.12}$$

This calculation takes into account the number of machine hours required per unit of weight (1 hour per pound) and the machine cost per hour (100 Euros per hour). The total production cost before overhead is given by the sum of all these costs, along with the development cost:

$$\begin{aligned}\text{total\_production\_cost} =& \text{material\_cost} + \\ & \text{labor\_cost} + \text{machine\_cost} + \text{development\_cost}\end{aligned} \tag{3.13}$$

The overhead factor is then applied to the *total production cost*, together with the *distance factor* and *frequency factor* in Eq.3.8, to obtain the *total manufacturing cost* of the landing gear. The approach described allows for a precise estimation of the landing gear's production cost by considering the primary factors involved, including material, labor, machine usage, and development costs. An important aspect is the overhead factor, which adds 20% to the direct costs to account for indirect expenses like management, rent, and essential services. The presented methodology not only offers a detailed calculation but also reflects the importance of customizing the model based on specific application parameters.

Fig. 3.4 illustrates the breakdown of manufacturing costs for the landing gear, revealing that a significant portion of the total manufacturing cost is attributed to labor and machine expenses, each accounting for €753,052.00. This is notably higher compared to material costs, amounting to €37,652.60. The development cost is relatively small at €20,000.00, suggesting that the major expenditures are concentrated on labor and machinery. The sum of these costs results in a total production cost of €1,563,756.60, while the total manufacturing cost, obtained applying the overhead factor, distance factor, and frequency factor, amounts to €4,571,567.36, reflecting the substantial investment required for the production of landing gear.

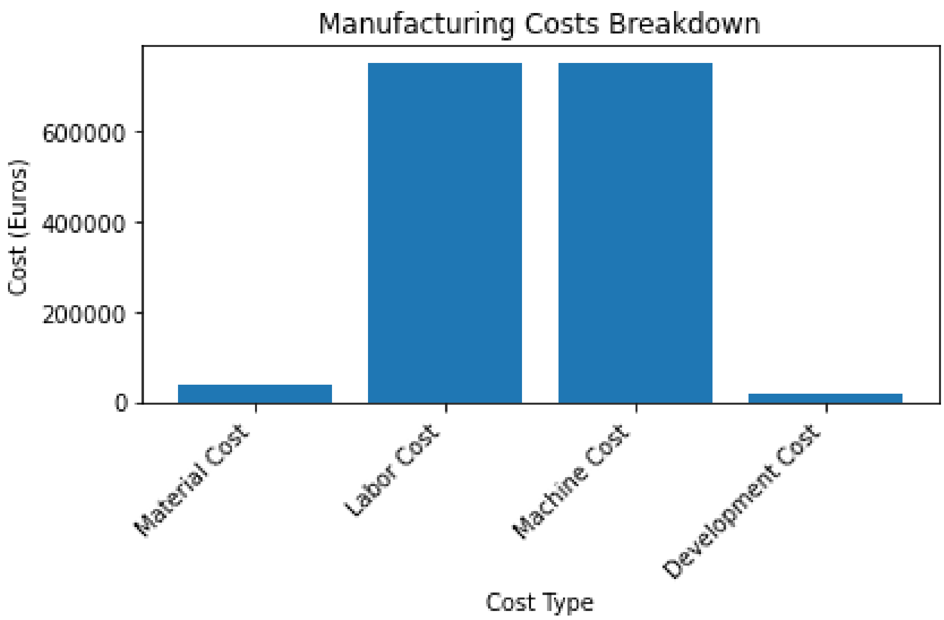

Figure 3.4: Manufacturing cost breakdown.

The costs associated with the use phase and end-of-life phase of the landing gear, already derived in chapter 2.3, are factored in, resulting in the comprehensive total cost for the landing gear, that is €9,712,340.42, as resumed in Tab. 3.6.

Cost Component	**Amount (€)**
Material Cost	37,652.60
Labor Cost	753,052.00
Machine Cost	753,052.00
Development Cost	20,000.00
Total Production Cost	1,563,756.60
Landing Gear Manufacturing Cost	4,571,567.36
Landing Gear Use Phase Cost	5,141,165.88
Landing Gear End Of Life Cost	-392.82
Total Landing Gear Cost	**9,712,340.42**

Table 3.6: Cost breakdown for the landing gear, including manufacturing, use phase, and end-of-life costs.

Chapter 4

Conclusion and Future Developments

4.1 Future Developments in LCA and LCC

The Life Cycle Analysis (LCA) and Life Cycle Cost (LCC) evaluation conducted for the landing gear offer important insights into the environmental and economic impacts of this component. However, significant advancements can still be made in this field. The methodologies used in this study address the manufacturing, use-operation, and end-of-life phases, but more sophisticated approaches could be employed. For instance, enhancing the manufacturing phase analysis with detailed material flows, process-specific emissions data, and supply chain impacts would lead to more accurate estimates. The use-operation phase could incorporate real-time monitoring and predictive analytics, enabling assessments that factor in flight conditions, fuel efficiency, and performance deterioration over time. The end-of-life phase would benefit from exploring innovative recycling technologies and more sustainable disposal pathways, considering the evolving materials used in the aerospace industry.

4.2 Gaps in Current Analysis: Maintenance, Energy Inputs, and Data Limitations

Despite the depth of the current analysis, notable gaps remain, particularly in areas critical to accurately modeling the lifecycle of landing gear. Maintenance activities, which are integral to the operational lifecycle, are not accounted for in this study. Regular inspections, replacements, and system upgrades have a considerable environmental and economic impact, which means their omission leaves a gap in the overall analysis. Furthermore, energy inputs, especially during manufacturing and operational phases, have not been fully integrated due to a lack of specific data. The energy consumed across different processes directly influences both emissions and costs, so excluding it limits the completeness of the LCA and LCC results.

A major limitation encountered in this study is the lack of accessible and reliable data. Much of the data required for precise calculations had to be estimated because detailed information from aircraft manufacturers and airlines is often proprietary. This lack of transparency highlights a key area for improvement: the establishment of an open-access database containing relevant lifecycle data for aerospace components. Such a resource would allow for more accurate and validated analyses, supporting research and industry-wide decision-making. This database could be maintained by regulatory bodies, industry consortia, or academic institutions, ensuring that it remains updated and comprehensive.

4.3 Feasibility of Results, Parametric Tools, and Future Research Directions

While the results obtained in this analysis provide a solid starting point, it's important to acknowledge that they are influenced by estimated data and simplified assumptions, which introduce a degree of uncertainty. Nevertheless, the study sets the groundwork for more detailed analyses. In addition to refining the current Python-based parametric tool, there is potential to develop even more advanced solutions. For instance, integrating machine learning models that adjust cost and emission predictions based on real-time operational data could significantly improve accuracy.

Moreover, integrating an open-access database with such parametric tools would enable dynamic and collaborative research, where industry professionals and academics can contribute and update data. Another avenue worth exploring is the integration of energy audits and maintenance data into the LCA and LCC assessments. By incorporating these previously overlooked elements, the analysis could better reflect the real-world operational conditions and costs. These advancements would ultimately lead to more comprehensive, scalable, and reliable assessments, driving better-informed decisions in the design, production, and lifecycle management of landing gear systems and other critical aerospace components.

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