UNIVERSITY OF PATRAS
DEPARTMENT OF MECHANICAL ENGINEERING & AERONAUTICS
DIVISION OF DESIGN & MANUFACTURING
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DIPLOMA THESIS

Contribution to an Engineering for Sustainability approach for aircraft conceptual design assessment

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ABSTRACT

Contribution to an Engineering for Sustainability approach for aircraft conceptual design assessment.

Charalampopoulou Vasiliki

The aviation industry faces increasing pressure to align with global sustainability goals, demanding a paradigm shift in how aircraft are conceptualized and evaluated. This thesis contributes to the development of an Engineering for Sustainability approach tailored to aircraft conceptual design by integrating sustainability and more specifically circular economy (CE) principles into early-stage assessment. The primary objective is to evaluate the CE potential of innovative aircraft configurations at the design stage, without altering the underlying designs, using relevant indicators. The research begins by identifying sustainability indicators from aviation literature, categorized across five pillars: performance, environment, cost, society, and circular economy and identifying the gap in CE assessment. A set of circularity indicators, aligned with ISO 59004 and structured under 13 Resource Management Actions (RMAs), is then selected and adapted for application at the aircraft level. Three aircraft configurations are assessed in a comparative case study: a conventional turbofan powered by fossil fuel (D250-TF-FF-2040), a turbofan using synthetic fuel (D250-TF-SF-2040), and a Mild Hybrid Electric Propulsion aircraft powered by liquid hydrogen (D250-TFLH2-MHEP-2040). Data for these indicators were extracted and processed from CPACS files, using specialized tools like RCE, enabling structured indicator integration and visualization, and from literature. Through a multi-scenario evaluation approach, incorporating equal, design-focused, and end-of-life-focused weighting strategies, the thesis demonstrates how circularity indicators can provide valuable insights into sustainable aircraft design trade-offs. Results show consistent performance rankings, with the MHEP-LH_2 concept achieving the highest circularity scores, validating the framework's robustness and potential application for comparative design assessments.

Key words

[Aircraft, Aviation Sustainability, Circular Economy, Assessment]

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ACRONYMS

CE	Circular Economy
CPACS	Common Parametric Aircraft Configuration Schema
EASA	European Union Aviation Safety Agency
FF	Fossil Fuel
SF	Synthetic Fuel
GHG	Green House Gas
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LH_2	Liquid Hydrogen
PHEP	Plug-In Hybrid Electric Propulsion
MHEP	Mild-Hybrid Electric Propulsion
PEMFC	Proton-Exchange-Membrane Fuel Cells
SAF	Sustainable Aviation Fuels
S-LCA	Social Life Cycle Assessment
TF	Turbofan
RCE	Remote Component Environment

CONTENTS

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1.0 INTRODUCTION

A significant threat to the globe is climate change, which is mainly caused by anthropogenic (human) greenhouse gas (GHG) emissions. The aviation sector is one of the significant contributors, and this sector is projected to increase at a very high level. The aviation industry often links the concept of sustainability to its environmental impact, focusing mainly on reducing emissions through technologies and the use of alternative fuels. However, sustainability is not only about environmental impact as there are other pillars that make it up. One of them is the Circular Economy (CE) which contributes to sustainability but is currently underexplored in the industry. In the aviation context, applying CE principles means designing aircraft systems to enable disassembly, reuse, recycling of parts, and reducing dependence on virgin materials. This thesis focuses on improving sustainability evaluation in aviation by integrating circular economy principles.

1.1 BACKGROUND AND MOTIVATION

Global warming is undoubtedly one of the most urgent problems these days. It is the result of increased CO_2 emissions and other Green House Gases (GHGs) emissions in the atmosphere. The climate change created by human activities accounts forming almost 20% of total (Allen et al., 2022). Besides aviation, other major sources of global warming include energy production, industrial manufacturing, agriculture, and land-use change. Aviation contributes about 3.5% of global warming effects when accounting for both CO_2 and non-CO_2 emissions (Ritchie, 2024). While this is relatively small compared to other sectors, it becomes significant due to projected fleet expansion and the high climate impact per unit of travel(Overton, 2022).

Therefore, the aerospace industry is increasingly acknowledging the necessity of shifting towards more sustainable practices, which will reduce its environmental impact as well as ensure long-term viability. According to Airbus, more than 42,000 new aircraft will be required in the next 20 years (AIRBUS, 2024a). This increases the urgency of embedding sustainability in early design stages.

A solution to this can be reached thought incorporating sustainability concepts like Circular Economy (CE) (Rodrigues Dias et al., 2022), which has been neglected up until now, especially in the aviation industry (ICAO Secretariat, 2019). CE is an approach aimed at extending product life, reducing waste, and maximizing material reuse across the value chain (ISO 59004, 2024). CE focuses on elimination of waste and pollution, material circulation and nature regeneration (Ellen Macarthur Foundation, 2024). It is a model that intends to the life cycle extension of the products and aims to replace the linear economic model, which is based on the purchase, use and discarding of a product.

1.2 GOAL AND OBJECTIVES

The main goal of this thesis is to assess the circularity performance of aircraft configurations using a framework based on CE principles, focusing on their applicability at the design stage without modifying the designs themselves.

The first part of this thesis consists of the following goals:

- Identification of existing sustainability indicators used in aviation literature across the five pillars of sustainability: performance, environment, cost, society, and circular economy.
- Selection and adaptation of circular economy (CE) indicators relevant to aircraft-level sustainability assessment, based on ISO 59004 and related works.
- A gap analysis identifying missing or underutilized data across existing aircraft datasets, with a focus on but not limited to the DLR-provided CPACS files.
- The application of weighting strategies to aggregate CE indicator scores for comparative evaluation across aircraft configurations.

After those goals are met, a comparative study of three aircraft configurations is conducted. The aircraft considered in this study have been developed by DLR in the framework of the project EXACT and EXACT 2, they represent three innovative aircraft configurations:

- D250-TF- FF-2040 - EXACT Turbofan Baseline using fossil fuel
- D250-TF-SF-2040 – EXACT Turbofan Baseline using synthetic fuel
- D250-TFLH2-MHEP-2040 – EXACT Mild Hybrid Electric propulsion configuration using LH_2.

The indicators and methods used for the CE assessment are defined in Chapters 4 and 5 and are applied in the comparative case study presented in Chapter 6.

1.3 STRUCTURE OF THE THESIS

This thesis is structured into seven core chapters and three appendices to guide the reader through the development, adaptation, and evaluation of sustainability and circularity indicators at the aircraft level.

- Chapter 1: Introduction
  Provides background and motivation for incorporating sustainability and circular economy (CE) principles in aviation. It outlines the goals and objectives of the study.
- Chapter 2: Literature Review
  Presents an overview of sustainability in aviation, highlighting various sustainability-related indicators across performance, cost, environment, society, and circular economy. It also explores methodologies and tools commonly used in sustainability assessments such as LCA, LCC, and S-LCA.
- Chapter 3: Case Study – Analysis of Sustainability Indicators from the EXACT Project
  Describes the aircraft configurations considered in the study (turbofan, synthetic kerosene-powered, and LH_2-fueled hybrid aircraft). It includes a gap analysis to identify missing or underutilized indicators within the available data.
- Chapter 4: Adapting Circularity Indicators for Aircraft
  Focuses on the adaptation of existing CE frameworks to the aviation context. It

introduces a set of indicators categorized under 13 Resource Management Actions (RMAs) and details their application to aircraft-level evaluation.

- Chapter 5: Methodology
  Details the processes of indicator selection, data collection, evaluation, scoring, and aggregation into final circularity scores for each aircraft configuration.
- Chapter 6: Results
  Provides the outcomes of the comparative assessment for three aircraft cases based on different weighting strategies: equal weighting, design-focused, and end-of-life-focused.
- Chapter 7: Conclusions and Recommendations
  Summarizes the key findings and provides suggestions for future research in sustainable aircraft design and CE integration.

2.0 LITERATURE REVIEW

2.1 OVERVIEW OF SUSTAINABILITY IN AVIATION

In aviation, sustainability is typically discussed in terms of environmental impact, focusing particularly on emissions and fuel efficiency, while also triggering research interest and policy discussions on climate change, air pollution and resource depletion. Efforts are now directed toward reducing these impacts across the entire lifecycle of aircraft. The International Air Transport Association (IATA) provides a list of necessary actions that need to be taken to achieve this goal (IATA, 2024). Some of the proposed measures include the replacement of conventional fuels, the reduction of inflight energy and carbon capture.

Furthermore, major manufacturers such as Boeing and Airbus have introduced sustainability strategies in areas like eco-efficient production, sustainable materials, and reduced emissions across aircraft lifecycles ((AIRBUS, 2024b; BOEING, 2024)). Their primary goal is the decarbonization of the aviation industry and the reduction of the environmental impact of this sector, following the Fly Net Zero by 2050 guidelines ((IATA, 2024)). Some of their targets are to switch to renewable electricity, make their fleet SAF compatible, and introduce hydrogen powered and hybrid propulsion systems. Also, both of them have implemented various sustainability initiatives. On the environmental side, they focus on decarbonizing operations and reducing lifecycle emissions through the use of alternative fuels, cleaner propulsion technologies, and more efficient aircraft designs. Separately, their social sustainability efforts target employee health and safety, as well as inclusiveness and diversity in the workplace. While most sustainability efforts in aviation focus on reducing the environmental impact, a system can be considered sustainable only if it addresses multiple dimensions in an integrated manner. (Filippatos et al., 2024), define sustainability through a holistic approach in the scope of aircraft design that considers long-term impacts and requires balancing multiple objectives. It encompasses five key pillars, which provide a broader perspective on sustainability of the product. Those are:

- The performance pillar describes the effectiveness of a product in relation to its similar substitutes in the market with regards to technical efficiency, effectiveness in operations and reliability. An aircraft should also be safe, and structurally sound through its lifecycle to be deemed as high performing

- The environmental pillar deals with the environmental impact that a product has during its whole lifecycle, from raw material extraction to end-of-life.
- The circular economy pillar is focused on the adoption of the closed-loop system, where the materials and components can be reused, refurbished or recycled at the end-of-life rather than discarded.
- The economic pillar is linked with the financial analysis of the system throughout the lifecycle that consists of manufacturing, operating, maintaining, and end of life cost. It makes sure that the product is economically viable to achieve targets of sustainability.
- The social pillar deals with the effects of the product on the people and society at every lifecycle phase. This includes indicators such as fair labor conditions, worker health and safety, community noise exposure, and the public acceptance of emerging technologies like hydrogen or electric propulsion.

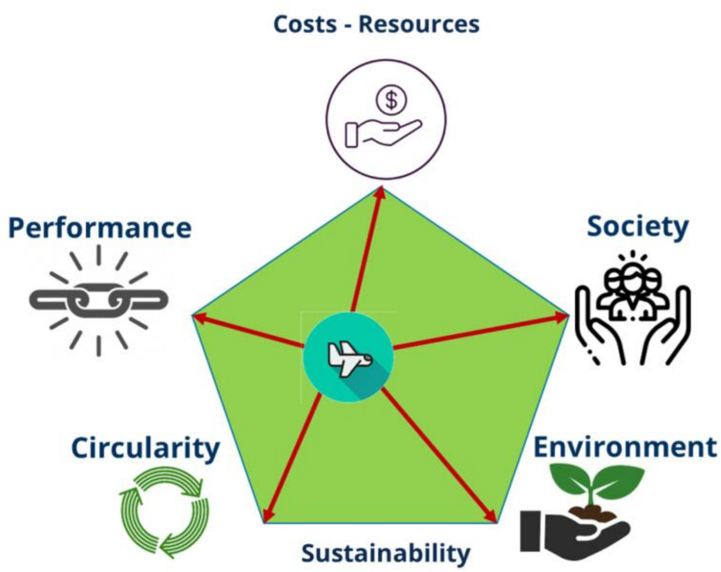

Figure 1: The five pillars of sustainability (Filippatos et al., 2024)

2.2 OVERVIEW OF SUSTAINABILITY-RELATED INDICATORS IN AVIATION

For the evaluation of the sustainability pillars, indicators are used, which are described in detail in this chapter. This chapter presents a review of relevant indicators and includes studies that assess aircraft based on the five sustainability dimensions introduced in chapter 2.1, which have been considered. These studies refer to aircraft used for passenger transportation. The indicators used by each study are presented in detail in Table 1.

Table 1: Sustainability related indicators based on literature.

Authors	**Criteria Comparison/Output**
(See et al., 2004)	Speed, max cruise range, capacity
(Listes & Dekker, 2005)	Load factor, Spill, Revenues, Operating costs, Fleet cost, Profit
(Čokorilo et al., 2010)	Technological (aerodynamic efficiency, structural efficiency, fuel flow at the optional FL, cruise endurance and requested trip fuel for the fixed cruise range), operational (max range with max payload, ground efficiency (aircraft maintainability based on external dimensions) and climb capability
(Ozdemir et al., 2011)	Purchasing Cost, Delivery Time, Dimensions Operation and Spare Cost Useful, Life Security, Maintenance Cost, Reliability Salvage Cost, Suitability for Service Quality
(Weiss et al., 2012)	MTOW, max. payload, Noise, GWP, AP, Land-use, Abiotic resource depletion, Direct operating costs, No. of crew members, Cabin comfort
(Sun et al., 2011)	Max cruise speed (Mach), MTOW, Available seat mile, Cabin volume per passenger, Fuel consumption per seat mile
(Dožić & Kalić, 2014)	Price of aircraft, payment conditions, CASM, seat capacity, total baggage, MTOM
(TEOH & KHOO, 2015)	Load factor, Passengers carried, RPK, ASK, Fuel Efficiency
(Bruno et al., 2015)	Unit operational costs, Aircraft price, Autonomy, Cruise speed, Cabin luggage compartment size, Seat comfort, Environmental pollution, Noise
(KİRACI & BAKIR, 2018)	Range, Price, Speed, Seating capacity, Fuel consumption, Maximum payload, Amount of greenhouse gas release
(Kiracı & Akan, 2020a)	Fuel Consumption Per Seat Mile, Range, Speed, Useful Life of the Aircraft, Landing and Take-Off Distance, Maximum Take-Off Weight, Aircraft Seat Capacity, Maintenance Cost, Salvage Cost, Operating Cost, Price of Aircraft, Pollution, Noise
(Rasaizadi et al., n.d.)	Price, Maximum Takeoff Weight (MTOW), Passenger Capacity, Fuel Capacity, Volume of Passengers' Space, Volume of Cargo Compartment

Prabowo und Zagloel (2022), (Prabowo et al., n.d.)	MTOW (Maximum Take-Off Weight), Payload, Range, Fuel Consumption, Take-Off Distance, Landing Distance, Price, Maintenance Cost, Population, Fleet Commonality
Güntut and Gökdalay (2023), (GÜNTUT & GÖKDALAY, 2023a)	Range, Carrying Capacity, Fuel Efficiency, Auxiliary Equipment, Spare Part Availability, Technical Support, Maximum Take-Off Weight, Utilization Period, Price, Demand, Finance Options, Aircraft Similarity, Cost per Available Seat Mile (CASM), Internal Rate of Return, Embargo Considerations, Foreign Policy, Noise, CO2 Emissions
(Ramm et al., 2024)	Speed, PAX, Payload, Range, ASK, Landing/Takeoff Distance, OEW, Useful life, Total flight hours, Total Distance, Total flight cycle, approach speed, GWP, NO_x emissions, H_2O emissions, contrails, LCCB, Operational cost, Component reuse, Resale value, Component recycling potential, Reuse rate.

The last paper mentioned in Table 1, uses results from a research program conducted at DLR called EXACT, which aims to produce aircraft using new technologies and alternative fuels. In this study, cost and environmental assessment of three aircraft configurations has been conducted. Their evaluation focused primarily on performance, environmental, and cost indicators. Although some reuse and recycling metrics were mentioned, they were not formally framed within a circular economy framework. Those were: Component reuse, Resale value, Component recycling potential, Reuse rate.

The frequency charts shown in the following figures reflect a selected sample of peer-reviewed studies identified using targeted keyword searches on aviation sustainability and aircraft design in Scopus and Google Scholar.

An analysis of the reviewed literature reveals an uneven distribution of sustainability indicators across the five pillars. Performance and cost indicators are cited most frequently, followed by environmental metrics, while society and circular economy indicators are much less common. This section details the indicators used under each pillar.

Table 2, highlights the indicators mentioned most frequently in the reviewed literature.

Table 2: Most frequent indicators

Performance	Environment	Cost	Society	Circular Economy
Maximum Takeoff Weight (6)	CO_2 emissions (3)	Price of the aircraft (7)	Cabin comfort (3)	Recycled mass percentage (1)
Range (6)	Noise emissions (4)	Operating Cost (5)		Component reuse (1)
Mach Number (5)		Maintenance Cost (3)		Resale value (1)

Payload (6)		CASM (3)		Component recycling potential (1)
PAX (5)				Reuse rate (1)

An analysis of the indicators referenced in the reviewed literature reveals an uneven distribution among these pillars. Based on Table 1, all the papers reviewed have one common point the evaluation an assessment of the aircraft based on performance characteristics (Figure 2). Three of these papers ((Čokorilo et al., 2010; Rasaizadi et al., 2021; See et al., 2004)) are assessing the aircraft based only on the performance pillar, while the other papers ((Bruno et al., 2015; Dožić & Kalić, 2014; GÜNTUT & GÖKDALAY, 2023b; KİRACI & BAKIR, 2018; Kiracı & Akan, 2020b; Listes & Dekker, 2005; Ozdemir et al., 2011; Prabowo et al., 2022; Rasaizadi et al., 2021; Sun et al., 2011; TEOH & KHOO, 2015; Weiss et al., 2012)) are using a combination of different pillars of sustainability. For example, in (Dožić & Kalić, 2014; Ozdemir et al., 2011), the aircraft have been assessed with indicators related to cost, society and performance pillars. As shown in the Figure 2, Performance indicators are dominating, followed closely by Cost. One can also observe that Society and the Environment are less frequently mentioned, and Circular Economy is underrepresented.

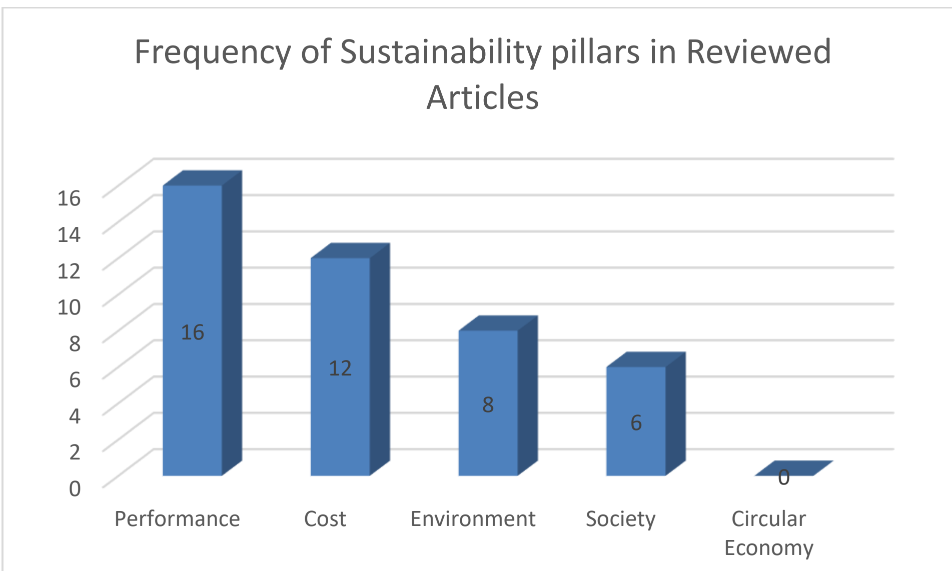

Figure 2: Distribution of Performance, Cost, Environment, Society, and Circular Economy Indicators in Aircraft Evaluation Literature.

2.2.1.1 PERFORMANCE INDICATORS BASED ON LITERATURE.

Performance indicators, Figure 3, assess multiple technical aspects and reflect important roles in measuring efficiency, reliability, and functional effectiveness for aircraft sustainability. These indicators influence key design and operational decisions such as aircraft configuration choices, propulsion system selection, and efficiency trade-offs.

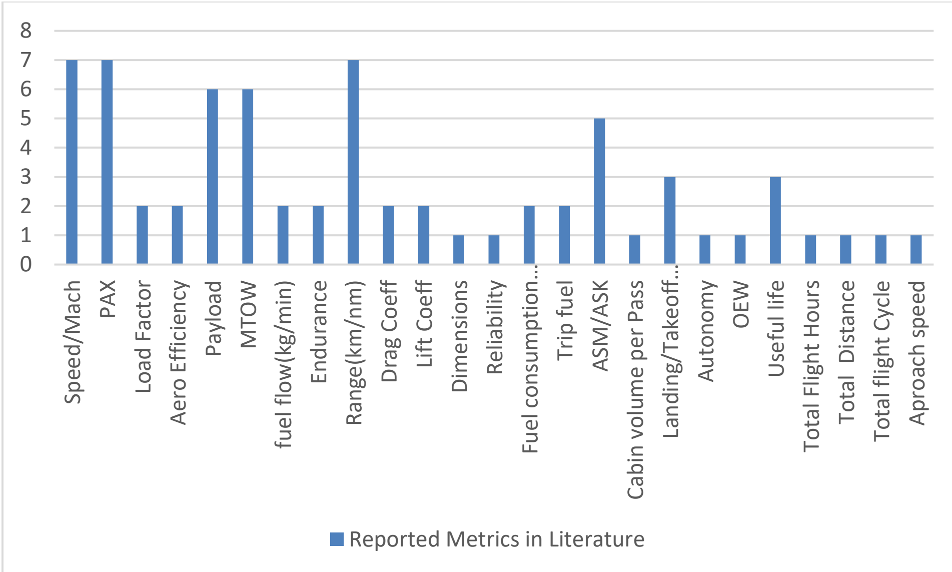

Figure 3: Frequency of occurrence of performance indicators in literature.

2.2.1.2 ENVIRONMENTAL INDICATORS BASED ON LITERATURE.

Figure 4 displays the frequency of the environmental indicators found in the literature. Aircraft design and operation affect emissions, fuel and resource consumption, and environmental quality. The identified indicators provide a basic representation of the society pillar; however the limited number of available studies does not allow current research to fully encompass this dimension of sustainability in aviation.

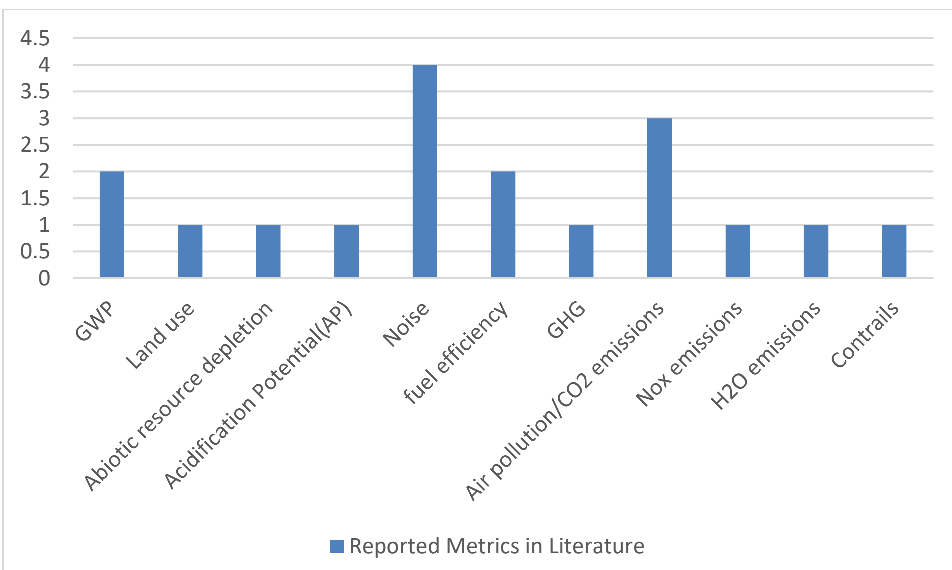

Figure 4: Frequency of occurrence of environmental indicators in literature.

2.2.1.3 COST INDICATORS BASED ON LITERATURE.

Cost indicators evaluate the financial performance and economic feasibility of aircraft across their lifecycle. Commonly used indicators in the literature include acquisition cost, operating cost, maintenance cost, and Cost per Available Seat Mile (CASM). These reflect both direct and indirect financial impacts on airlines and manufacturers. As illustrated in Figure 4, operating cost and acquisition cost are among the most frequently cited, with CASM appearing in a smaller number of studies. The focus on these indicators highlights the industry's interest in economic efficiency, especially given the capital-intensive nature of aircraft design and operation.

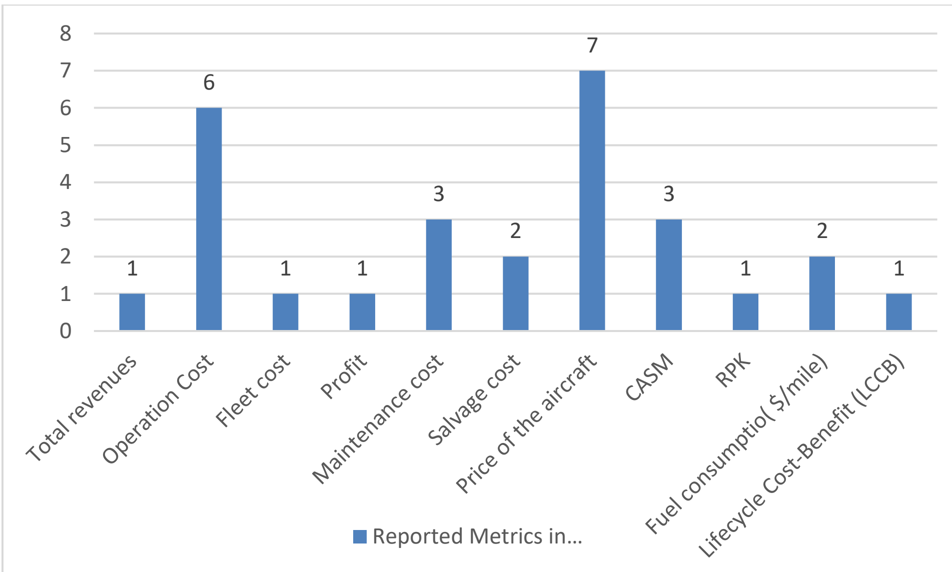

Figure 5: Frequency of occurrence of cost related indicators in literature.

2.2.1.4 SOCIETY INDICATORS BASED ON LITERATURE.

Society indicators, Figure 6, focus on social impacts such as passenger comfort, noise pollution, and community well-being. Based on the limited number of reviewed studies, there appears to be a relatively lower emphasis on social sustainability indicators in aircraft design and operations.

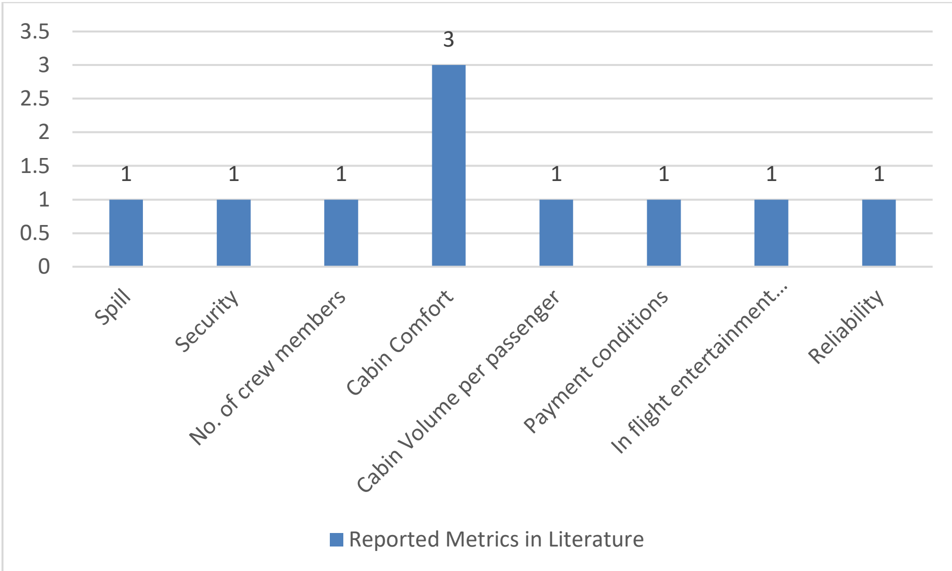

Figure 6: Frequency of occurrence of society related indicators in literature

2.2.1.5 CIRCULAR ECONOMY INDICATORS BASED ON LITERATURE.

CE indicators, Figure 7, emphasize material recycling, reuse, and lifecycle optimization, key components of a circular approach. The limited number of circular economy indicators used underscores the gap in fully integrating these principles into aircraft design, assessment methodologies, and decision-making across the entire lifecycle.

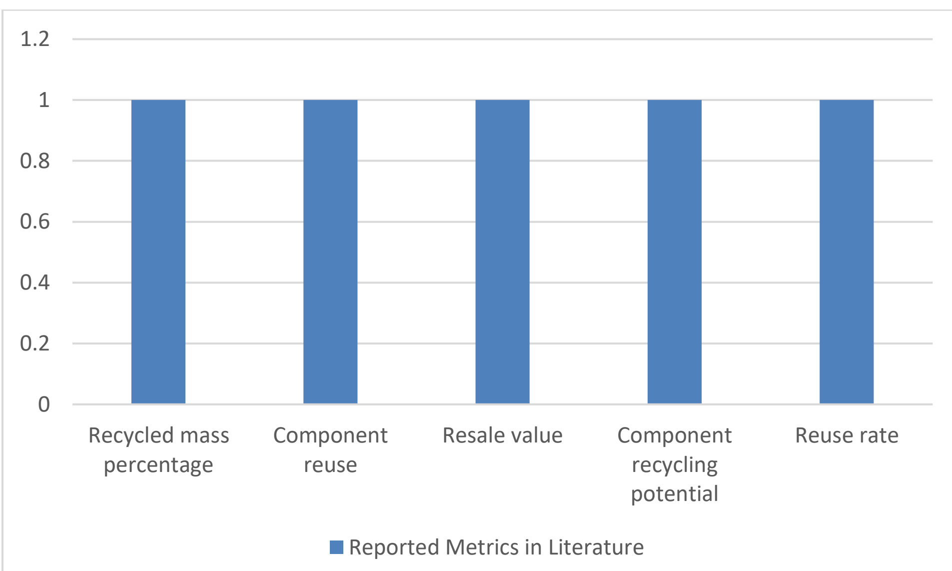

Figure 7: Frequency of occurrence of CE indicators in literature.

2.3 PREVIOUS WORK ON CE INDICATORS

As mentioned in 2.2.1.5, the CE pillar in aircraft level evaluation is underrepresented, but it is gaining traction over the last years. Studies and projects are exploring the implementation of CE in aviation, considering a vast variety of topics from resource efficiency to waste management.

(Bachmann et al., 2021) aimed to examine the material selection for interior and secondary structures considering their entire lifespan, their recyclability, and ability to be reused. In this research, the need to incorporate damage detection methods and easy repair at the preliminary stages of design is highlighted, so as to extend the lifecycle of the product and reduce the material waste.

The future Sky joint research program from (EREA, 2019), highlights the importance of adopting a new perspective about maintenance, production and end of life phases that are often neglected when considering ways to improve the circularity of the system. Furthermore, a report drafted for a global network of advisory services (Brown et al., 2024), emphasizes that waste and resource reduction are crucial factors in CE. In the same report innovative technologies like AR and VR are considered essential in improving the disassembly process.

From an economic perspective, the cost of reused parts is particularly important, as they are typically around 30% less expensive than newly manufactured components. Additionally, the cost of repairs plays a critical role in the viability of CE strategies in aviation. Also, as noted (Sustainair, 2022), while repairs can extend a product's lifespan and support CE, such strategies may become economically unviable if repair costs are excessively high. Additionally, although LCA impact categories do not explicitly measure circularity, they can still support circular economy strategies by identifying which life cycle stages—such as manufacturing, operation, or end-of-life—contribute most to environmental burdens and therefore offer opportunities for circular interventions like reuse, recycling, or design for disassembly.

Last but not least, recently a methodology has been proposed for assessing CE principles within the aviation industry (Paletti et al., 2025). This methodology provides a more holistic approach for circularity assessment, covering the majority of the areas mentioned above.

2.4 OVERVIEW OF METHODS AND TOOLS FOR ASSESSING SUSTAINABILITY-RELATED ASPECTS OF AIRCRAFT

Life cycle-based approaches have been widely developed since the 1990s to assess sustainability across various sectors. The most established frameworks are Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), which evaluate environmental, economic, and social impacts respectively (International Organization for Standardization., 2006; International Organization for Standardization, 2017). While the combined application of these three methods is still uncommon in aircraft design practice, they provide a foundation for selecting sustainability indicators relevant to different lifecycle stages. For this reason, individual metrics drawn from these frameworks were adapted in this thesis to evaluate circular economy performance.

Life Cycle Assessment (LCA) is defined by ISO 14040 and ISO 14044 as a method for compiling and evaluating the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle — from raw material acquisition through production, use, and disposal (cradle to grave).(Fabre et al., 2022). Social Life Cycle Assessment (S-LCA), as outlined in the UNEP 2020 Guidelines, evaluates the social impacts of products and services across their life cycle. It focuses on stakeholder groups such as workers, local communities, consumers, and society at large. Typical aspects assessed include labor conditions, health and safety, access to services, community well-being, and human rights (Burchart & Przytuła, 2024). This methodology examines aspects, including labor conditions, community engagement, and responsible sourcing practices(Burchart & Przytuła, 2024).

Of the three methodologies, only Life Cycle Assessment (LCA) follows a fully standardized four-phase model, defined in ISO 14040 and ISO 14044: (1) Goal and Scope Definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation, as shown in Figure 8. Throughout the first phase, called Goal and Scope Definition, the purpose and the boundaries of the analysis are defined. The second phase i.e. the Inventory analysis refers to data collection and evaluation. In the third phase, called Impact Assessment, the potential environmental, social, and economic impacts are evaluated based on methodologies that are proper for LCA, LCC, and S-LCA. Each method differs across all stages—particularly in the type of data used and the way impacts are assessed—reflecting their distinct environmental, economic, and social objectives. The final phase, called Life Cycle Interpretation, includes the interpretation of the results and the conclusions derived by them.

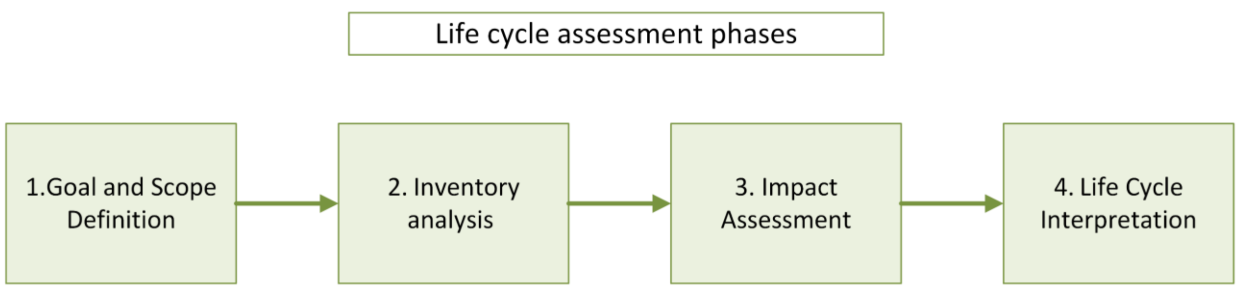

Figure 8: The four phases of a life cycle assessment.

3.0 CASE STUDY: ANALYSIS OF SUSTAINABILITY-RELATED INDICATORS FROM THE EXACT PROJECT

3.1 DESCRIPTION OF THE AIRCRAFT AND TECHNOLOGIES CONSIDERED

3.1.1 DATA SOURCE

The data used in this thesis derive from the results obtained via the EXACT project. EXACT stands for Exploration of Electric Aircraft Concepts and Technologies and is a study conducted by the German Aerospace Center (DLR). In this research project, a wide variety of aircraft configurations were designed, modeled, and evaluated based on performance, emissions, and sustainability-related criteria, with each configuration featuring a distinct propulsion system. The EXACT project followed a second project, known as EXACT2, which upgraded the existing work with updated aircraft configurations and refined assessment methods. In the original (EXACT) project, an extensive aircraft design space had been investigated with a diversity of energy carrier, power and thrust provider and operational concept technologies. Additionally, the full aircraft life cycle—including manufacturing, operation, and end-of-life stages—had been considered in the assessment of each configuration.

3.1.2 TYPES OF AIRCRAFT

EXACT led to the development of four main aircraft configurations, depicted in Figure 9. The first one is the turbofan aircraft configuration [1], which is a conventional short-haul aircraft that can be powered by fossil fuels and synthetic kerosene. What differentiates it to today's short-haul aircraft is the increased aerodynamic efficiency, CFRP implementation in the structure, all electric on-board system architecture and Ultra-high bypass ratio turbofan engine (DLR, 2025). The second one is a turboprop aircraft configuration [2], powered by both synthetic and fossil kerosene, which shows significant efficiency improvements compared to the conventional turbofan powered baseline concept for kerosene scenarios (DLR, 2023). This option offers a low-risk solution without making major changes to infrastructure and technologies, reducing climate impact by more than 40% with fossil kerosene, and between 50% and 90% with synthetic kerosene compared to the most efficient short-medium range aircraft operating today. The third aircraft configuration [3] is the Plug-In Hybrid Electric Propulsion (PHEP) aircraft which is capable of relying only on batteries for short-haul trips, up to five hundred kilometers, and for longer trips is powered by a gas turbine which allows it to extend its range up to 2800 kilometers. This concept is both economically and ecologically viable for a short-range aircraft designed for 250 passengers.

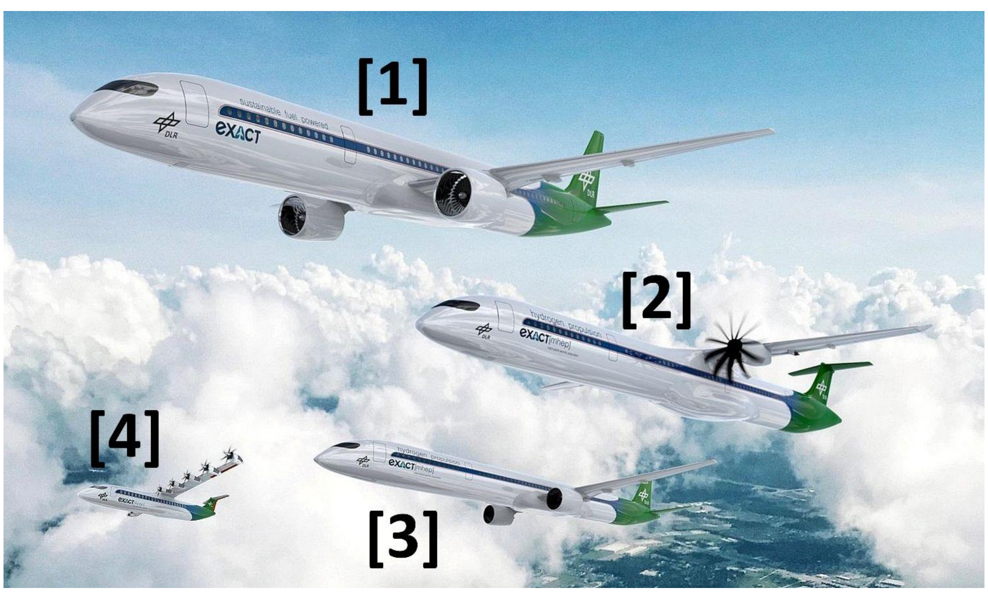

Figure 9: EXACT configurations: [1] turbofan, [2] turboprop, [3] Plug-In Hybrid Electric Propulsion (PHEP), [4] Mild-Hybrid Electric Propulsion (MHEP)(DLR, 2023)

Additionally, it demonstrates the greatest potential for climate impact reduction (over 70%) when powered by fossil kerosene, compared to the most efficient short- to medium-range aircraft in use today. The last aircraft configuration is the Mild-Hybrid Electric Propulsion (MHEP) aircraft concept which utilizes two conventional gas turbines as the primary power source. During off-design phases of the mission, such as taxiing and descent, proton-exchange-membrane fuel cells (PEMFC) replace the gas turbines, also providing power for onboard systems. This design enables optimization during off-design operations, resulting in substantial energy savings for missions under 1800 kilometers. The MHEP architecture is adaptable to both turbofan and turboprop propulsion systems.

In this thesis three use cases will be analyzed which are based on three different short-range aircraft concepts, Figure 10. Those are the MHEP (D250-TFLH2-MHEP), the conventional turbofan aircraft fueled by synthetic kerosene (D250-TF-SF), and the conventional turbofan aircraft fueled by fossil kerosene (D250-TF- FF).

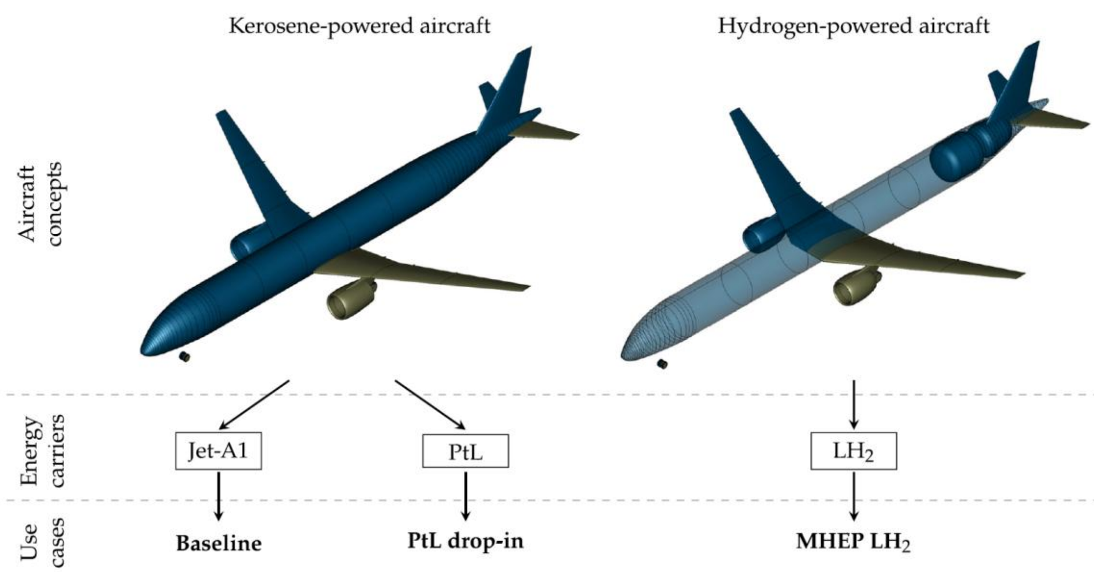

Figure 10: aircraft configurations. (Ramm et al., 2024)

All aircraft can carry 250 passengers and a maximum payload of 25 tons over a range of 1500 NM with a design cruise Mach number at 0.78. The main differences are the energy carrier and the secondary power provider. The conventional turbofan configuration can be fueled with either of synthetic or fossil fuel, and the MHEP with Liquid Hydrogen (LH_2). Synthetic kerosene can serve as a drop-in replacement for fossil kerosene, requiring no major modifications to existing aircraft or fueling infrastructure. However, its production remains energy-intensive and costly due to the low efficiency of current Power-to-Liquid (PtL) processes and the high electricity demand for hydrogen generation via electrolysis (Ramm et al., 2024). On the other hand, LH2 has higher production efficiency compared to synthetic kerosene, but its liability lies in its price and storage difficulties. In the conventional turbofan aircraft, secondary power is provided by the engines, whereas in the MHEP by a fuel cell-based auxiliary power unit (APU+) (shown in Figure 11). The APU+ system, which includes Proton-Exchange Membrane Fuel Cell (PEMFC) stacks and their subsystems (Schröder et al., 2021), offers significant advantages over conventional auxiliary power units by reducing both greenhouse gas and local pollutant emissions during ground operations.

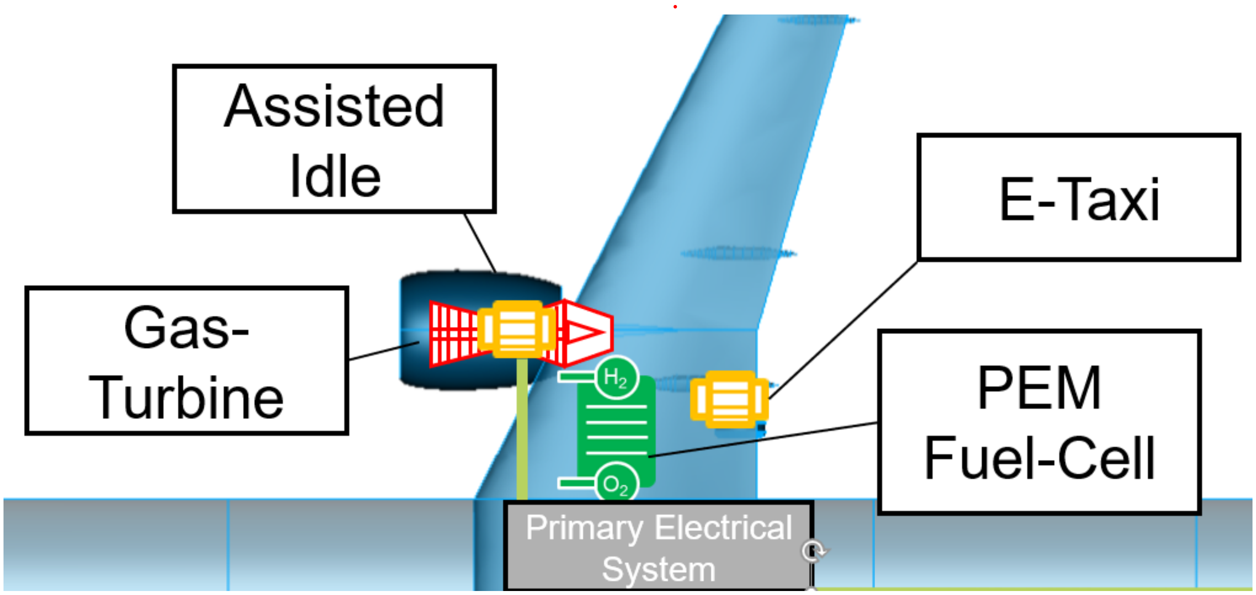

Figure 11: Mild-Hybrid-Electric Propulsion architecture(Silberhorn, 2025)

Each vehicle consists of a number of subsystems organized in modules and submodules. The exact structure of the modules and submodules is derived from the corresponding CPACS files. Based on these files, modules refer to basic aircraft systems like power unit , while submodules refer to the systems of these modules like nacelle and gas turbine. A detailed list of them for each aircraft configuration is presented in Table A. 1.

3.1.3 DATA STORAGE, INTEGRATION, AND VISUALIZATION

The design details of the configurations discussed in the previous section can be found in Common Parametric Aircraft Configuration Schema (CPACS) files (DLR, 2025). CPACS is a standardized data exchange format, designed for collaborative aircraft design projects, which provides a way to share information between many disciplines and many teams working on aircraft design. The XML Schema Definition allows CPACS to be human-readable, as well as computer-processable. In these files detailed parametrization for multiple aircraft components is included, such as fuselage and wing.

The CPACS files are readable with a set of tools and programming interfaces, including TiXI or Python-based parsers, allowing them to read and operate on the XML structure. The valid structure and content of a CPACS file are described by a related XML Schema Definition (XSD) file, which serves as a template to guarantee that each data entry has the same format, structure, and naming scheme. An open-source software named RCE (Remote Component Environment) allows users to access HTML-based documentation generated from the schema to search the CPACS hierarchy and to discover information about each tag (Alder et al., 2020).

The DLR has created an application (RCE) that assists engineers in the integration and implementation of multidisciplinary engineering processes. It lets the user modulate various disciplinary tools and declare dependences among them. RCE stores data in one place to be analyzed and carried out after processing, which increases the effectiveness of cooperation among engineers. It can run workflows on distributed networks of computed nodes and automatically parallelizes the use of independent tools to increase performance (Boden et al., 2021). The RCE interface is shown in Figure 12.

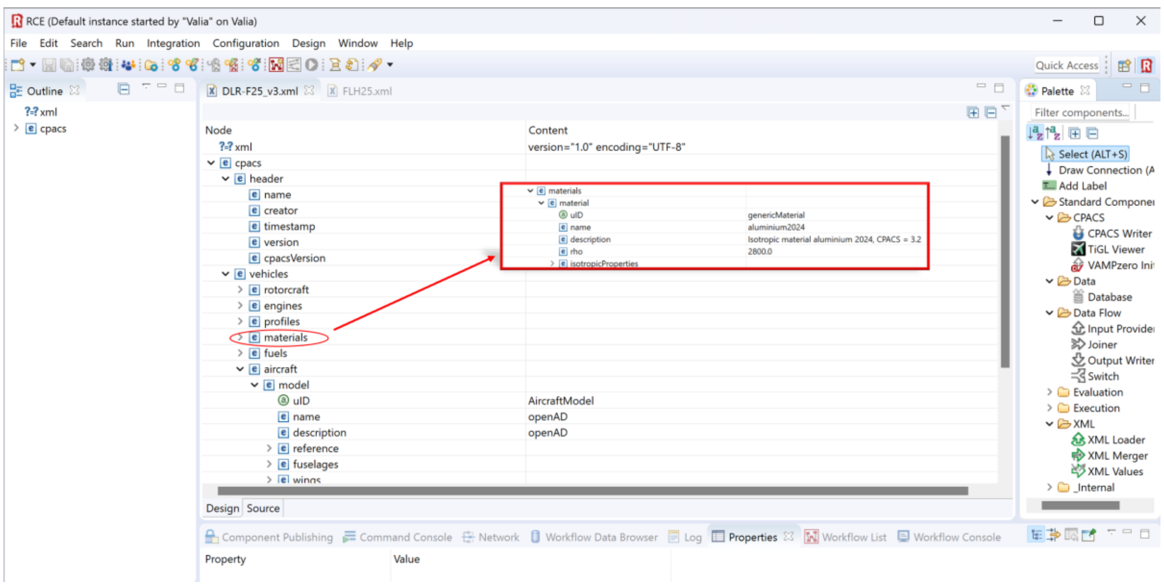

Figure 12: RCE interface.

Additionally, CPACS files can be visualized as 3D aircraft models using TiGL (Figure 13), an open-source computational geometry library that generates geometry from CPACS design parameters. This library is primarily used during the conceptual and preliminary phases of aircraft design to create detailed models (Siggel et al., 2019).

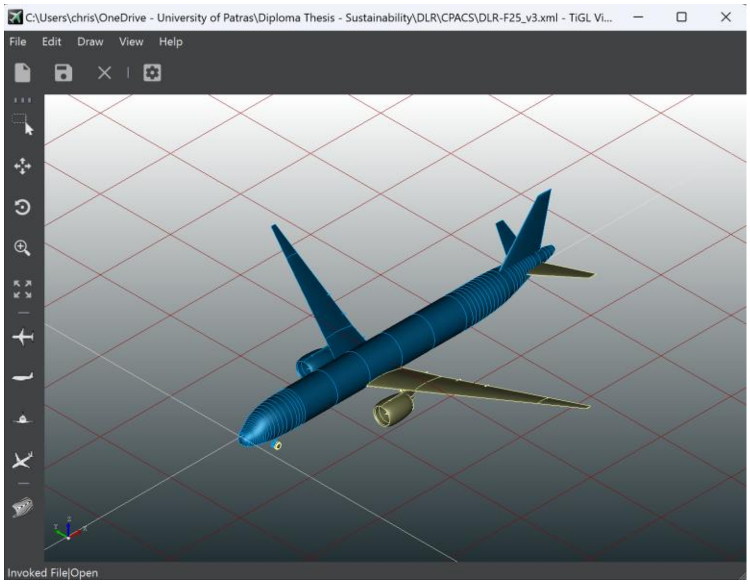

Figure 13: TiGL viewer interface.

3.2 GAP ANALYSIS OF MISSING OR UNDERUTILIZED INDICATORS

This chapter aims to examine whether the indicators used to assess the sustainability of aircraft that were identified in chapter 2.2 can be quantified based on the data (CPACS files) derived from EXACT DLR. In Figure 14 the indicators are presented and separated based on the five pillars of sustainability.

The value of some of those indicators can be found directly in the CPACS files. However, other indicators are not explicitly present in the CPACS files but can be derived from the data they contain. Lastly, there are some indicators that can be calculated or quantified only based on literature.

For better understanding of the sources of the indicators used in this assessment, a color-coded system has been used in Figure 14. This categorization clarifies the relationship between the indicators and their sources. Indicators in green represent those that can be found within the CPACS files and can be used without further computation. Indicators in red signify those that cannot be found or calculated within the CPACS files. These indicators can be sourced only from literature. Yellow is used to indicate indicators that can be derived through calculations based on CPACS files and literature. Lastly, indicators displayed in grey have already been calculated within the EXACT project; those values are used for this assessment.

Performance	Society	Cost	Environment	Circular Economy
Speed/Mach PAX Payload MTOW Fuel flow Range Drag Coeff. Lift Coeff. Dimentions Landing/Takeoff Distance OEW Approach speed			CO_2 emissions NOx emissions H_2O emissions	
Aero Efficiency Fuel consumption per seat mile		Cost Per Available Seat Mile (CASM) Revenue Passenger Kilometers (RPK) Fuel consumption		
Endurance Reliability Cabin volume per passenger Useful life	Spill Security No. of crew members Cabin comfort Cabin volume per passenger Payment conditions In-flight entertainment systems Reliability	Total revenues Operation Cost Fleet cost Profit Maintenance cost Salvage cost	Noise Fuel efficiency Air pollution/CO_2 emissions H_2O emissions Contrails	Recycled mass percentage Component reuse Component recycling potential Reuse rate
Load factor Trip fuel Available Seat Miles(ASM) Total Flight Hours Total Distance Total flight cycle		Price of the aircraft	GWP Land use Abiotic resource depletion Acidification Potential (AP)	

Figure 14: Color coded list of indicators used to assess the sustainability of aircraft across the five pillars.

3.3 IDENTIFICATION OF RELEVANT INDICATORS FROM THE EXACT PROJECT

In Table 3, the values of the indicators presented in Figure 14 with green, those that can be found in the CPACS, will be quantified.

Table 3: Data available in CPACS files

Performance	D250-TF- FF	D250-TF- Sf	D250-TFLH2-MHEP	Unit
Speed/Mach	0.78	0.78	0.78	-
PAX	250	250	250	-
Payload	25	25	25	t

MTOW		81.3	81.3	82.1	t
Range		1500	1500	1500	NM
Drag Coeff		0.0347	0.0347	0.0335	-
Lift Coeff		0.613	0.613	0.566	-
Dimensions	Wing Area	110.4	110.4	125.1	m
	Wingspan limit	36	36	36	m
Trip Fuel/ Block fuel		7579.2	7579.2	2687.2	kg
Takeoff Distance		1900	1900	1900	m
OEW		47.5	47.5	54.8	t
Approach speed		140	140	140	kt

4.0 ADAPTING CIRCULARITY INDICATORS FOR SELECTED AIRCRAFT

4.1 METHODOLOGY

Based on (Paletti et al., 2025) and the above literature review a list of indicators is defined. The indicators selected for assessing the circularity of an aircraft are categorized following the 13 Resource Management Actions (RMA) defined by ISO 59004.These RMAs are not focused only on waste reduction and recycling but also include resource and design considerations. The definitions of each RMA used in this thesis apply the terminology established in ISO 59004:2024 and are explained in the ensuing pages.

4.2 PROPOSED CIRCULARITY INDICATORS FOR AIRCRAFT-LEVEL EVALUATION

In this chapter, the selected indicators are presented, analyzed, and defined. The number of indicators varies across RMAs, as shown in Figure 15, simply because it has been particularly challenging to identify relevant circularity indicators for actions such as Cascade and Repurpose. This difficulty stems from the lack of established use cases and indicators at the aircraft level, as these actions typically involve reassigning components to lower-value or non-aerospace applications, making performance evaluation and traceability more complex.

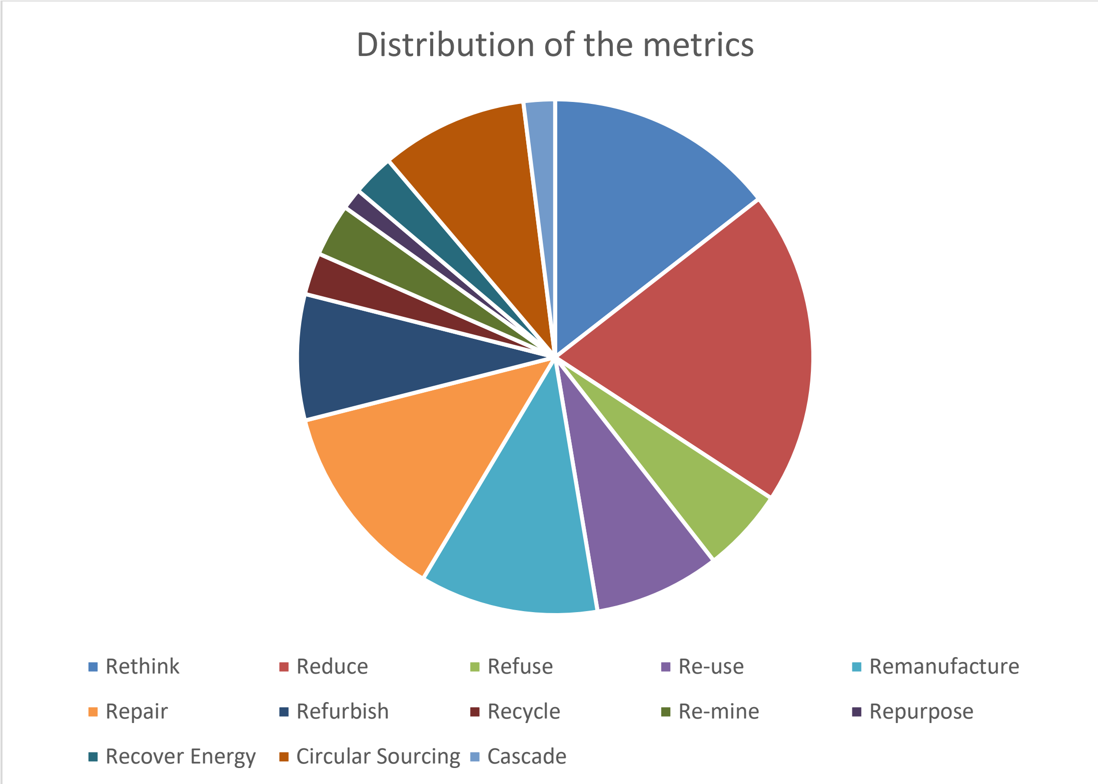

Figure 15:Distribution of the indicators across the RMAs.

Since D250-TF-SF and D250-TF-FS have the same configuration, in the assessment, the indicators that are not related to the fuel type are treated in the same way and indicated a as a single category named D250-TF.

4.2.1 REFUSE

This action aims to eliminate the need for specific solutions or products. In some cases, this means completely giving up a function—for example, phasing out fossil kerosene-fueled aircraft. In other cases, the same function is preserved, but achieved through different means, such as replacing fossil kerosene with synthetic fuel.

4.2.1.1 PERCENTAGE OF FOSSIL, SYNTHETIC FUEL AND LH_2 TO POWER THE AIRCRAFT NO.0001- NO.0003

The aviation industry, as already mentioned, contributes to CO_2 emissions, in a large percentage due to fuel consumption (Zhou, 2024). Therefore, the less the emissions produced during fuel combustion, the more circular the fuel option is. The three configurations are fueled with fossil kerosene (D250-TF- FF), synthetic kerosene (D250-TF- SF) and liquid hydrogen (LH_2) (D250-TFLH2-MHEP) respectively.

4.2.1.2 PROPULSION TYPE - NO.0004

Propulsion type plays significant role in propulsion efficiency. Hybrid-electric propulsion systems allow the engines to operate closer to their optimal efficiency points more often and enable more efficient aircraft configurations(Ramm et al., 2024). Hence, when an aircraft uses hybrid electric propulsion system it is more circular than one that uses a jet propulsion system.

The D250-TF uses jet propulsion system, whereas the D250-TFLH2-MHEP has a hybrid-electric propulsion system, consisting of gas turbines and PEMFC. The PEMFC replaces the gas turbines during Taxi-out, Take-Off, and Descent.

4.2.1.3 PRESENCE OF ELECTRIC TAXIING - NO.0005

By incorporating electric taxiing into aircraft design, a significant fuel reduction can be achieved during taxiing(Groot & Roling, 2022). Out of the three configurations only the D250-TFLH2-MHEP has an electric taxiing system(Silberhorn, 2023).

4.2.1.4 PRESENCE OF ID ON COMPONENT, PRODUCT - NO.0006-7

ID is a unique identifier that is used to provide easy localization of the components/products either in maintenance or end-of-life. So, it facilitates the process and ensures that nothing is lost. Therefore, the presence of ID improves the circularity of the system. The ID of each component and aircraft can be found in the CPACS files of each configuration.

4.2.1.5 PERCENTAGE OF RECYCLED MATERIALS - NO.0008

Using recycled materials is important for achieving a CE system, because it promotes the maximum use of resources. All configurations use newly manufactured components and virgin materials, so the percentage of recycled materials is 0% for all of them.

4.2.2 RETHINK

This action involves re-evaluating the decisions made during the design process of a product; for example, the type of materials used for manufacturing (recycled or not). It also includes the concept of making a multifunctional product.

4.2.2.1 PERCENTAGE OF PRODUCT FOLLOWING A SAFE LIFE APPROACH - RT.0001

Based on (Gunes, 2013), a safe-life approach is a way to address damage prevention at structures. This approach determines the life cycle of the structure during which it can be used safely. After the end of this period the product is retired, even if it is still in good condition. According to this, it is determined which of the parts of the configurations were designed based on this approach. Discarding a product (or part of) when it still serves its purpose undermines its circularity.

The values of this indicator for the configurations can be found in Table A. 2.

4.2.2.2 PERCENTAGE OF PRODUCT FOLLOWING A FAIL-SAFE APPROACH - RT.0002

Based on (Gunes, 2013), a fail-safe approach is a way to address damage prevention at structures. This approach is based on the logic that even if a part of the structure fails, the other parts of the structure are robust enough so they will not fail as well. According to this, it is determined which of the parts of the configurations were designed based on this approach.

The values of this indicator for the configurations can be found in Table A. 2.

4.2.2.3 PERCENTAGE OF PRODUCT FOLLOWING ANY STRUCTURAL INTEGRITY APPROACH - RT.0003

Structural integrity is important for every structure because most failures observed in structures, originally made to withstand loads, are due to fatigue(XIONG & SHENOI, 2019). So, it is critical to incorporate it in the designing process to prevent, as far as possible, damages. All configurations follow a structural integrity approach; forms an integral part of the designing process.

4.2.2.4 TIME NEEDED FOR MANUFACTURING - RT.0004

Manufacturing can be a time consuming and high pollutant process (Zacharia, 2025). Although less time does not explicitly mean less emissions or waste, reducing manufacturing time can reduce resource consumption and waste generation. This improves the circularity of a product. The D250-TF is based on the A320neo, so it can be assumed that it needs the same time to be manufactured. The calculation of the RT0004 for the A320neo is presented below:

- First year of release: 2016
- No. Delivered: 68 aircraft in the first year of release(AIRBUS, 2017)

Therefore, the time needed for manufacturing will be:

$$time\ for\ manufacturing = \frac{1\ year}{68\ aircraft} = \frac{8760\ hours}{68\ aircraft} = 128.8 \frac{hours}{aircraft}$$

<u>Hypothesis</u>: The No of MHEP aircraft delivered/manufactured in the first year of release will be half of the A320neo during the corresponding first year. So, the time needed for manufacturing for the MHEP will be doubled compared to the D250-TF.

4.2.2.5 TECHNICAL LIFETIME - RT.0005

The longer a product is at service the more circular it is. Technical lifetime is mentioned in (Ramm et al., 2024). The most circular aircraft of the 3 is the one with a longer technical lifetime.

4.2.2.6 PERCENTAGE OF COMPONENTS THAT HAVE A DIGITAL PRODUCT PASSPORT - RT.0006

Digital Product Passport (DPP) is a document introduced by the Ecodesign for Sustainable Products Regulation (ESPR) aiming to improve the circularity of a product (European Commission, 2024). A Digital Product Passport (DPP) supports CE by storing and sharing detailed data on a product's origin, material composition, maintenance history, and design specifications. This information enables more effective reuse, disassembly, recycling, and lifecycle tracking, as stakeholders can make informed decisions about the product's recovery, refurbishment, or end-of-life processing. Thus, it facilitates processes like recycling, repair and reuse. The percentage of components that have a Digital Product Passport is 0%, because DPP is not yet implemented.

4.2.2.7 PERCENTAGE OF MATERIALS WITH ANY TYPE OF SUSTAINABILITY CERTIFICATE (EPD, B-CORP...) - RT.0007

Sustainability certificates offer transparency on a product's origin, manufacturing etc. The higher the percentage of materials in a product that have a sustainability certificate, the more circular a material is. The percentage of materials with any type of sustainability certificate is 0%. This information is not yet implemented.

4.2.2.8 PERCENTAGE OF COMPONENTS (IN ONE PRODUCT) WITH ANY TYPE OF SUSTAINABILITY CERTIFICATE (EPD, B-CORP...) - RT.0008

The percentage of components (in one product) with any type of sustainability certificate is 0%. This information is not yet implemented.

4.2.2.9 PERCENTAGE OF NEWLY MANUFACTURED COMPONENTS - RT.0009

Using newly manufactured components undermine the principles of circular economy that aims to reduce the need for new resources since manufacturing new components requires raw material extraction. So, the higher the percentage, the less circular the product is. All components are newly manufactured for all three aircraft, so the percentage of newly manufactured components is 100% for all three of them.

4.2.2.10 PERCENTAGE OF REFURBISHED COMPONENTS - RT.0010

Using refurbished components improves circularity because it contributes to the elimination of new materials and waste. Refurbished are the components that have been processed in order to restore the product itself or a part of it to a like new condition. (Zacharaki et al., 2021)The higher the percentage is, the more circular the component is. The percentage of refurbished components is 0% for all the configurations because of RT.0009.

4.2.2.11 PERCENTAGE OF REMANUFACTURED COMPONENTS - RT.0011

Using remanufactured components improves the circularity, so the higher the percentage is, the more circular the component is. Remanufactured are the components that have been processed in order to restore the product itself or a part of it to an as-new condition (Zacharaki et al., 2021), and it requires full disassembly, cleaning and replacement of worn parts. The percentage of remanufactured components is 0% for all the configurations because of RT.0009.

4.2.2.12 PERCENTAGE OF PRODUCT THAT FOLLOW ECO-DESIGN PRINCIPLES - RT.0012

This indicator is determined based on the 'eco-design requirements'(European Commission, 2024). Those requirements aim to make products more sustainable, while the application of eco-design is indicated (Ellen Macarthur Foundation, 2025) to support circular economy. So, the higher the achieved percentage the more circular a product is. To each one of the requirements can be assigned value 0 or value 1. When the value is one (1), it means that the examined configuration is better than the A320neo aircraft in that specific requirement, whereas when the value is zero (0), it means that there are no significant differences, compared to that.

Table 4: Ecodesign principles

Ecodesign requirements	D250-TF		D250-TFLH2-MHEP
	Fossil Fuel	Synthetic Fuel	
Improving product durability	0	0	0
Improving product reusability	0	0	0
Improving product upgradability	0	0	0
Improving product reparability	1	1	0
Enhancing the possibility of product maintenance	1	1	0
Enhancing the possibility of product refurbishment	0	0	0
Making products more energy	1	1	1
Making products more resource-efficient	1	1	1
Addressing the presence of substances that inhibit circularity	0	1	1
Increasing recycled content	0	0	1
Making products easier to remanufacture	0	0	0
Making products easier to recycle	0	0	1
Setting rules on environmental footprints	1	1	1
Setting rules on carbon footprints	0	1	1
Limiting the generation of waste	0	0	1
Improving the availability of information on product sustainability	0	1	1
Percentage of product that follow Ecodesign principles	**31.25**	**50**	**56.25**

No 4: APU systems are getting repaired compared to the Fuel Cell APU systems, because the Fuel Cell APU systems have not yet been manufactured on an industrial scale and remain at the conceptual phase.

No 5: Maintenance tasks are not standardized for the MHEP, so this configuration does not enhance the possibility of product maintenance.

No 7: All three configurations were designed to be more energy than the A320neo.

No 8: All three configurations were designed to be more and resource efficient than the A320neo. The D250-TF has improved fuel efficiency compared to A320neo, because it uses an ultra-high bypass ratio turbofan engine (DLR, 2025). Furthermore, the D250-TFLH2-MHEP integrates fuel cells with two gas turbines, enabling more efficient use of fuel (DLR, 2025).

No 9: D250-TF- FF uses fossil kerosene as fuel which inhibits circularity especially compared to D250-TFLH2-MHEP and D250-TF- Synthetic Kerosene which use LH_2 and Synthetic Kerosene, respectively.

No 13 and 14: Because D250-TFLH2-MHEP and D250-TF- Synthetic Kerosene use fuels that do not pollute the environment as much, they have lower emissions during the in-flight operations.

No 16: The use of advanced technologies such as fuel cells, as well as alternative fuels such as SAF and LH_2, combined with more reliable on-board systems architectures, contribute not only to improving the energy efficiency of vehicles but also to advancing the availability of information on product sustainability.

RT.0012 is the percentage of requirements that each configuration meets and is calculated based on the formula below:

$$RT.0012 = \left(\frac{\sum_{i=1}^{n} x_i}{n}\right) * 100 \qquad [\%]$$

Where:

- x_i is the value for each Ecodesign requirement for the specific aircraft;
- n is the number of Ecodesign requirements.

4.2.2.13 PRESENCE OF BILL OF MATERIALS - RT.0013

Bill of Materials (BoM) is a document containing the information required for the manufacturing of a product, from raw materials to assembly line. The presence of BoM is important because it provides transparency, so if there is a BoM circularity is high. It is assumed that a BoM is available for all configurations.

4.2.2.14 NUMBER OF MANUFACTURING PROCESSES - RT.0014

In this assessment, the number of manufacturing processes is only evaluated for the APU, fuel tanks (kerosene/SAF and LH_2), and fuel-cell-based systems. This is based on the assumption that differences in the number of airframe-related manufacturing processes between the D250-TF and the MHEP are negligible and would not significantly affect comparative results. (Reference: Airbus A320 Aircraft Characteristics,

Table 5: Number of manufacturing processes

	Conventional	MHEP
No manufacturing processes:	11	13

The number of manufacturing processes for each configuration was estimated based on CPACS-defined components and typical aerospace manufacturing steps. Key systems such as the APU, fuel tanks, and fuel cell stacks were considered. The MHEP configuration includes additional processes due to the integration of hydrogen and fuel cell systems, which require cryogenic and electrochemical manufacturing steps not present in the conventional design.

4.2.2.15 PRESENCE OF COATINGS - RT.0015

Some materials used in coatings are hazardous, a fact that undermines the circularity of a coated structure because a specific manufacturing process, and the end product is difficult to recycle or reused. In airframe structures aluminum is coated with Cr^{6+}, steel with cadmium and CFRP with resin (Baldwin & Smith, 1996; Johnson, 2015; OSHA, 2013). Also, there are coatings in the fuel cells, pipping etc. Hence, there are coatings in all three configurations.

4.2.2.16 USE OF MODELING TOOLS TO ASSESS PERFORMANCE AND ENVIRONMENTAL IMPACT OF MASS REDUCTIONS - RT.0016

Using modeling tools to simulate the impact of reductions offers great advantages, such as the ability to explore multiple alternatives and for the efficient identification an optimum solution. So, if they are used during the designing process circularity is improved. These tools have been used in all three configurations by DLR.

4.2.2.17 PRESENCE OF ADDITIVE MANUFACTURING PROCESSES - RT.0017

Additive manufacturing processes can be a great asset to CE because they minimize the amount of waste generated during manufacturing.

4.2.2.18 PRESENCE OF ELECTRIC TAXIING - RT.0018

See 4.2.1.

4.2.2.19 AVERAGE SERVICE HOURS AT TIME OF RETIREMENT, AGE OF PRODUCT AT TIME OF RETIREMENT - RT.0019-0020

As already mentioned, extending the lifespan of a product, and keeping it into service is important for CE. So, the longer a product is in use, the more circular it is.

Based on (AIRBUS, 2006): an A320 accumulates about 2,800 FH per year.

The lifespan of the aircraft is 32 years(Ramm et al., 2024).

Total Estimated Flight Hours Calculation (over lifespan):

$$(2800 \frac{FH}{year} * 32\, years) = 89600\, FH$$

$RT.0021 = 8960\, FH$ for all three configurations.

4.2.3 CIRCULAR SOURCING

This action promotes using sustainable, renewable, and recyclable resources to replace virgin materials and thus reduce raw material extraction.

4.2.3.1 PERCENTAGE OF VIRGIN MATERIALS - CS.0001

When the materials used are virgin, circularity worsens. All configurations use 100% virgin materials.

4.2.3.2 PERCENTAGE OF RECYCLED MATERIALS - CS.0002

See 4.3.1.5.

4.2.3.3 PERCENTAGE OF RECYCLABLE MATERIALS - CS.0003

When the materials used are recyclable the circularity improves. This metric measures the weight of each material as a percentage of the total weight of all materials, considering only those that are recyclable materials. The percentage of recyclable materials is calculated based on the equation below:

$$\text{CS}.0003 = 100 * \frac{\sum_j^n (C_j * B_j)}{\sum_j^n B_j}$$

Where:

- C_j is the binary value that defines if this material is recyclable or not;
- B_j is the weight of the j material;
- n is the number of the materials.

The percentage of virgin materials can be found in Table A. 4 and Table A. 5 in the appendix.

4.2.3.4 PERCENTAGE OF HAZARDOUS MATERIAL/CHEMICAL CONTENT - CS.0004

Apart from Tetrafluoroethylene which can be found in the PEMFC systems, the other materials used in the configurations are not hazardous per se. However, the coatings in some cases are. For example, it is known that aluminum aerostructures use Cr^{6+} coating, steel on the other hand has cadmium plating, CFRPs have resin coating and are all hazardous when processed. When the materials used are hazardous the circularity worsens. This metric measures the weight of each material as a percentage of the total weight of all materials, considering only those that are critical materials. The percentage of critical materials is calculated based on the equation below:

$$\text{CS.0005} = 100 * \frac{\sum_{j}^{n}(E_j * B_j)}{\sum_{j}^{n} B_j}$$

Where:

- E_j is the binary value that defines if this material is hazardous or not;
- B_j is the weight of the j material;
- n is the number of the materials.

The percentage of hazardous materials can be found in Table A. 4 in the appendix.

4.2.3.5 PERCENTAGE OF CRITICAL MATERIALS - CS.0005

Critical materials based on (European Comission, 2023), are the materials that combine raw materials of high importance to the EU economy and of high risk associated with their supply. This metric measures the weight of each material as a percentage of the total weight of all materials, considering only those that are critical materials. The percentage of critical materials is calculated based on the equation below:

$$\text{CS.0005} = 100 * \frac{\sum_{j}^{n}(D_j * B_j)}{\sum_{j}^{n} B_j}$$

Where:

- D_j is the binary value that defines if this material is recyclable or not;
- B_j is the weight of the j material;
- n is the number of the materials.

The percentage of critical materials can be found in Table A. 4 and Table A. 5 in the appendix.

4.2.3.6 PERCENTAGE OF CRITICAL RAW MATERIALS WHICH ARE RECYCLABLE - CS.0006

When the critical materials used are recyclable, the circularity improves. This metric measures the weight of each material as a percentage of the total weight of the critical materials, considering only those that are recyclable. The percentage of recyclable critical materials is calculated based on the equation below:

$$\text{CS.0006} = 100 * \frac{\sum_{j}^{n}(C_j * D_j * B_j)}{\sum_{j}^{n} B_j}$$

Where:

- D_j is the binary value that defines if this material is recyclable or not;
- B_j is the weight of the j material;
- C_j is the binary value that defines if the j material is recyclable or not;
- n is the number of the materials.

The percentage of critical raw materials can be found in Table A. 4 and Table A. 5 in the appendix.

4.2.3.7 PERCENTAGE OF RENEWABLE MATERIALS - CS.0007

When the materials used are renewable, circularity improves. This percentage is 0% because none of the materials presented in Table A. 4 and Table A. 5 are renewable.

4.2.3.8 PERCENTAGE OF COMPONENTS (IN ONE PRODUCT) WITH ANY TYPE OF SUSTAINABILITY CERTIFICATE (EPD, B-CORP...) - CS.0008

See 4.2.2.8.

4.2.3.9 PERCENTAGE OF MATERIALS WITH ANY TYPE OF SUSTAINABILITY CERTIFICATE (EPD, B-CORP...) - CS.0009

See 4.2.2.7.

4.2.3.10 PRESENCE OF COATINGS - CS.0010

See 4.2.2.15.

4.2.3.11 PERCENTAGE OF FUEL USED - CS.0011,13-14

See 4.2.1.1

4.2.3.12 PERCENTAGE OF NATURAL FIBERS USED IN COMPOSITES - CS.0012

When the fibers used in the composites are natural, the circularity improves. This percentage is 0% % because none of the composites presented in Table A. 4 and Table A. 5 have natural fibers.

4.2.4 REDUCE

This action is intended to increase efficiency in product manufacture or use by consuming fewer natural resources and materials (International Organization for Standardization., 2024).

4.2.4.1 PROPULSION COMPOSITION - RD.0001

See 4.2.1.2.

4.2.4.2 PRESENCE OF ELECTRIC TAXIING - RD.0002

See 4.2.1.3.

4.2.4.3 NUMBER OF SUB-MODULES - RD.0003

A high number of submodules can affect circularity in many ways. Having a large number of sub-modules makes disassembly more complex and time consuming. Also, when a product is composed of many different modules, separating those modules for recycling becomes significantly more difficult and costly. This is because recycling processes often rely on separating module's materials into their individual components for effective processing and reuse. The presence of multiple modules, especially when their materials are combined or layered in complex ways, can hinder or even prevent effective separation, leading to reduced recycling efficiency and potential contamination of the recycling stream (Jacobs et al., 2022). So, the lower the amount of sub-components needed for a product, the more circular the product is. The number of modules can be found in Table A. 1.

4.2.4.4 TOTAL ENERGY NECESSARY FOR MANUFACTURING - RD.0004

Circular economy aims to reduce the resources and energy used; so, it is important to design products that require the least possible energy during manufacturing. The energy for manufacturing is computed based on MMC S1 spreadsheet from (Rahn et al., 2025). In Table A. 6, the value for the amount of energy D250-TF is presented while in Table A. 7 the value for the D250-TFLH$_2$-MHEP.

4.2.4.5 PRESENCE OF BILL OF WASTE, BILL OF ENERGY - RD.0005, 0007

The Bill of Waste (BoW) and Bill of Energy (BoE) provide detailed documentation about waste and energy consumption. Tracking the waste generated can help identify areas where resources are not effectively used. Also, tracking energy consumption can help identify processes that consume an excessive amount of energy proposing improvements. It is crucial that these documents become available for reasons of transparency and assistance in decision making that will render future products more circular. Those documents are not available at this stage.

4.2.4.6 NUMBER OF MANUFACTURING PROCESSES - RD.0006

See 4.2.2.14.

4.2.4.7 PRESENCE OF BILL OF MATERIALS - RD.0008

See 4.2.2.13.

4.2.4.8 NUMBER OF DIFFERENT MATERIALS - RD.0009

The number of different materials is an indicator of how complex the product is for processing, since different materials require different joining techniques, which in turn can make disassembly more demanding and undermine the recycling/sorting processes.

The materials of each module are simplified. Only the materials contributing more than 10% of the weight are considered except for the fuel cells materials that do not exceed this limit. The latter, however, constitute a submodule that differentiates strongly these two configurations, and for that reason their materials have been incorporated. Overall, this indicator is an estimate of the actual number and is determined based on the materials mentioned in each module, Table A. 1.

4.2.4.9 TOTAL WEIGHT (MTOW) - RD.0010

The lighter an aircraft, the less fuel is needed to operate, and the less resources are used to manufacture it. So, the configuration with the smallest weight will be considered the more circular. The data for this indicator come from the CPACS files of each configuration (DLR, 2025)

4.2.4.10 PERCENTAGE OF VIRGIN MATERIALS - RD.0011

See 4.3.3.1.

4.2.4.11 PERCENTAGE OF RECYCLED MATERIALS - RD.0012

See 4.2.1.5.

4.2.4.12 PERCENTAGE OF RECYCLABLE MATERIALS - RD.0013

See 4.3.3.3.

4.2.4.13 PERCENTAGE OF HAZARDOUS MATERIAL/CHEMICAL CONTENT - RD.0014

See 4.3.3.4.

4.2.4.14 LCA INDICATORS RD.0015-0017

LCA assesses the entire lifecycle of a product, from raw material extraction to EoL; as such, it is a valuable contributor to the assessment of circularity. In this thesis, the impact categories (midpoints) resulting from an LCA will not be used as indicators. Instead, the LCA indicators are based on endpoints that summarize the impact of midpoints on three key axes of protection:

- Human health
- Natural environment
- Natural resources

The process of aggregation of these impact categories was done as follows:

1. Each impact category was assigned to one or more of the three endpoints based on Figure 16.

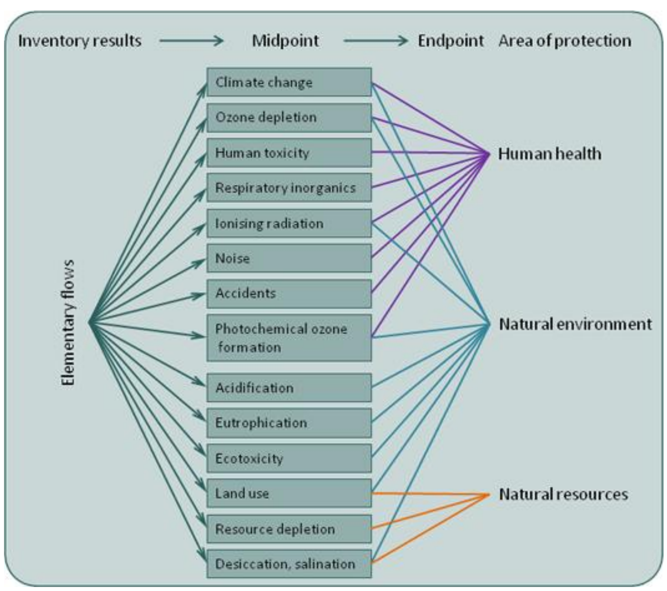

Figure 16: LCA impact categories (European Commission, 2025)

2. For each impact category an individual rating was calculated to make the values comparable. The values for the LCA impact categories were given by internal DLR source.

3. For each endpoint the average of the scores of all the categories was calculated that make up the endpoint:

$$Rating_{endpoint} = \frac{\sum_{i=1}^{n} Rating_{category\ i}}{n}$$

Note: All categories were assigned equal weight within their endpoint group.

Table 6 shows how the impact categories were distributed across those 3 endpoints.

Table 6: Endpoints-Midpoints-LCA impact categories

Endpoint	Midpoints	
Natural resources	Water Use	User deprivation potential (deprivation weighted water consumption)
	Energy Carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)
	Land Use	Soil quality index
	Mineral and Metals	Abiotic resource depletion (ADP ultimate reserves)
RD.0015		
Natural environment	Climate Change	Radiative forcing as Global Warming Potential (GWP100)
	Acidification	Accumulated Exceedance (AE)
	Freshwater Ecotoxicity	Comparative Toxic Unit for ecosystems (CTU_e)
	Freshwater Eutrophication	Fraction of nutrients reaching freshwater end compartment (P)
	Marine Eutrophication	Fraction of nutrients reaching marine end compartment (N)
	Terrestrial Eutrophication	Accumulated Exceedance (AE)
	Ozone Depletion Potential	Ozone Layer Depletion
	Ionizing Radiation	Human exposure efficiency relative to U^{235}
	Photochemical Ozone Creation	Tropospheric ozone concentration increase
RD.0016		

Human health	Carcinogenic Effects	Comparative Toxic Unit for humans (CTU_h)
	Ionizing Radiation	Human exposure efficiency relative to U^{235}
	Ozone Depletion Potential	Ozone Layer Depletion
	Photochemical Ozone Creation	Tropospheric ozone concentration increase
	Respiratory Effects	Human health effects associated with exposure to $PM_{2.5}$
	Climate Change	Radiative forcing as Global Warming Potential (GWP100)
RD.0017		

4.2.5 REPAIR

Repair seeks to restore damaged or defective products, so they function safely and properly for a longer period. Furthermore, this action prevents useful products from going to waste, so it satisfies multiple CE goals.

4.2.5.1 RESOURCES (SUBSTANCES, MATERIALS, TOOLS, ...) FOR MAINTENANCE - RP.0001

Maintenance is one of the most cost demanding phases(Alomar & Yatskiv, 2023) and it is essential for the safe operation of the aircraft. Using the right tools to complete the maintenance facilitates the process and ensures that the product will be maintained in a safe state. Therefore, knowing how much stuff is required for each maintenance task, offers resource efficiency and less waste. This information is not available at this stage.

4.2.5.2 PERCENTAGE OF AIRCRAFT EQUIPPED WITH SHM SYSTEMS - RP.0002

Structural Health Monitoring (SHM) systems are systems that can predict the damage of a structure by analyzing real-time data coming from loading and damaging conditions of a structure. Incorporating them into the design can prevent damage occurring during flight. So, having those systems increases the circularity of the product. None of the configurations have SHM systems.

4.2.5.3 SAFETY ASSESSMENT OF THE AIRCRAFT - RP.0003

The failure rate for the D250-TF can be estimated as it is based on the A320 aircraft, which is already in service and meets the safety standards. In contrast, for the MHEP, which is based on technology that has not yet been evaluated in aircraft, it is not easy to determine and compare the failure rate. For this reason, this indicator will be defined based on the TRL (Technology Readiness Level) of each configuration. This indicator enables a quantitative evaluation of the level of development and implementation of technology(Mankins, 1955). The higher the TRL, the more circular the configuration.

As already mentioned, the D250-TF is based on the Airbus A320neo, which has been successfully produced and operated since 2016, so the TRL for this configuration is assumed to be 9. The MHEP configuration is conceptual and incorporates technologies that are under development. So, it is assumed that the TRL for this configuration is 2.

4.2.5.4 PERCENTAGE OF COMPONENTS WHICH CAN BE REPAIRED (THEORETICAL) - RP.0004

There are some components that are not repairable, for a variety of reasons. For example, they might not have been designed with the possibility of disassembly or the specific material that consists of this component cannot be repaired. Therefore, the higher the percentage of components which can be repaired the more circular the product is, as it prolongs its lifetime.

4.2.5.5 TIME NEEDED FOR REPAIR - RP.0005

Although repair, as already mentioned, is particularly important for extending the lifespan of a product, it should also be time efficient. Therefore, the less time the repair requires, the more circular the product is. The information is not available at this stage.

4.2.5.6 PRESENCE OF INSPECTION SCHEDULE – RP0006

The inspection schedule is required to make sure that the aircraft continues to operate safely as long as possible. Maintaining the product in good condition, thus extending its lifespan, is a significant factor that boosts circularity. The values for this indicator are obtained from Table 5, A4 and A5 from ((Ramm et al., 2024)).

4.2.5.7 TIME TAKEN TO DISMANTLE THE PRODUCT (TOTAL) - RP.0007

This indicator is defined on the basis of manhours and not hours required for dismantling an aircraft. Manhours account for both the number of people involved and time required, thus they provide a more accurate measure of the process's intensity. Based on (SUSTAINair, 2023), the time needed to dismantle an aircraft is 2500-3200 manhours depending on its size. If the conventional turbofan (D250-TF), which is based on the A320neo, is a medium sized aircraft, the manhours needed to dismantle it are 2850.

The D250-TFLH2-MHEP is also a medium sized aircraft, but it has different fuel tanks and APU system. So, the manhours for this will be 2850 plus the time needed for the new systems. Using the data from (Ramm et al., 2024), the time needed to dismantle the LH2 tank, and the Fuel cell stack are presented in Table 7:

Table 7: Manhours required for replacement of LH_2 systems and exchange of fuel cell stacks and subsystems

Task	Manhours
Replacement of LH_2 tank	26700
Exchange fuel cell Stacks and subsystems	120

Time needed to dismantle the LH_2 tank:

$$\frac{26700}{2} = 13350\ manhours$$

Time needed to dismantle the fuel cell Stacks and subsystems:

$$\frac{120}{2} = 60\ manhours$$

Total amount of time needed to dismantle the D250-TFLH2-MHEP: 16260 manhours.

4.2.5.8 USE OF ADDITIVE MANUFACTURING PROCESSES - RP.0008

See 4.2.2.17.

4.2.5.9 POSSIBILITY OF OVERHAUL - RP.0009

Overhaul is an extensive maintenance process where the product gets disassembled, inspected, repaired, and restored. It extends the lifespan of the product, so it promotes the circularity of the product. There is possibility of overhaul across all three configurations.

4.2.5.10 PRESENCE OF DOCUMENTATION - TRACEABILITY OF REPAIR - RP.0010

Tracking repair history improves maintenance efficiency by reducing diagnostic time and avoiding redundant repairs. Moreover, having a complete repair record facilitates component reuse, as it increases confidence in the part’s reliability and simplifies decisions about refurbishing or recycling. Therefore, the presence of this documentation improves the circularity of a product. This kind of information is not available at this stage.

4.2.5.11 PERCENTAGE OF LIFE CYCLE EXTENSION ACHIEVED THROUGH OPERATION MAINTENANCE STRATEGY - RP.0011

Life cycle extension is one of the primary goals of CE. So, the higher this percentage is, the more circular the product is. All aircraft are maintained, however the percentage extension through maintenance is not available because the data regarding the lifetime of the aircraft without maintenance are not available.

4.2.5.12 MAINTENANCE COST - RP.0012

Although maintenance as already mentioned is particularly important for extending the lifespan of a product, it should also be cost efficient to be economically viable. Therefore, the less expensive the maintenance cost is, the more circular the product is. The total maintenance cost is presented in Table 8.

Table 8:Total maintenance cost for all three configurations.

	Total maintenance cost

D250-TF-FF	4893463.247
D250-TF-SF	
D250-TFLH2-MHEP	6520803.845

4.2.5.13 REPAIR BY USER - RP.0013,

Repair by user contributes significantly to enhancing circularity by reducing dependence on external repair providers, which leads to savings in resources such as energy, time, and manpower. The convention is that the user is the company that owns the product and the company's specialized stuff. There are some repair tasks, i.e., minor repairs to avionics, which are performed by the airlines by themselves, so this indicator would get the value yes for all aircraft.

4.2.5.14 REPAIR BY SPECIALIZED STAFF - RP.0014

When specialized staff performs repair, it means that more resources are needed, so it undermines the circularity of the product. External companies perform the majority of heavy repair tasks, so this indicator would get the value yes for all aircraft.

4.2.5.15 PERCENTAGE OF THE PRODUCT WHICH CAN BE DISASSEMBLED (DISASSEMBLY OR DEMOUNTABILITY) - RP.0019

Disassembly, as already mentioned in 4.2.5.4, is a process that is necessary for repairs. If the product cannot be disassembled, it is difficult to access all the parts of it and repair the damage. For that reason, it is important that design for disassembly is incorporated during the designing process. The higher the percentage is, the more circular the product is. The percentages for each product are presented in Table A. 3.

4.2.5.16 POSSIBILITY OF DETECTION OF DAMAGE OR FAILURE - RP.0021

This indicator, unlike the one in 4.2.5.2, typically involves non-destructive methods such as visual inspection or thermography (Ulus et al., 2024), but it can also be implemented through embedded sensor systems. While it identifies existing damage, it does not predict future failures. All configurations have the possibility of damage detection.

4.2.6 RE-USE

Re-use aims to use a discarded item which is still in working condition for its initial purpose. This action helps in preserve the value of the parts and the energy required for manufacturing.

4.2.6.1 PERCENTAGE OF THE PRODUCT THAT CAN BE REUSED RE.0001

A high percentage improves the circularity of the aircraft. The reuse rate has been calculated based on the contribution of each material to the individual modules of the aircraft. More specifically, for each module, the following have been considered: the reuse rate of the corresponding material, as derived from the literature, multiplied by the weight of the material within the specific module. The sum of these values for all modules is divided by the total weight of the aircraft, to derive the reuse rate of the aircraft. The results are presented in Table A. 9 and Table A. 10.

A high percentage improves the circularity of the aircraft. The percentage of the product that can be reused is calculated based on the equation below:

$$RE.0001 = \frac{(\sum_{i=1}^{n} m_i * f_i)}{\sum_{i=1}^{n} m_i} \quad [\%]$$

Where:

- m_i is the mass of each material of each module of each aircraft;
- f_i is the percentage of the mass of the i material, which is allocated for reusing;
- n is the total number of materials for all the modules of each aircraft.

4.2.6.2 PERCENTAGE OF REUSE OF OTHERS' (RECOVERED) PRODUCTS RE.0002

This indicator refers to the percentage the aircraft that consists of components that have been recovered from other aircraft. It is important for a product to reuse others' recovered products because it reduces the dependence on new resources and promotes the closed loop stream. All three configurations use newly manufactured components, so the percentage is 0% for all of them.

4.2.6.3 PERCENTAGE OF MODULARITY ACROSS PRODUCT RE.0003

Modularity across product refers to the design of submodules so that they can be used to different type of products families. This enhances component reuse and promotes CE. This information is not available, because the configurations are conceptual, hence is unknown what products will be available when they get into service and how they could use the components of these configurations.

4.2.6.4 PERCENTAGE OF MODULARITY ACROSS PORTFOLIO - RE.0004

Modularity across portfolio refers to the design of products with common modules, submodules between different models of the same manufacturing line. This enhances component reuse and promotes CE. To evaluate the modularity across portfolio, each submodule is examined separately. If a submodule is common in two or three aircraft, it is assigned a score of 1. If a submodule exists only in one out of three aircraft, it is assigned a score of 0. The percentage of modularity across portfolio is calculated based on this formula:

$$\mathrm{RE.0004} = \frac{number\ of\ common\ submodules}{total\ number\ of\ submodules} \quad [\%]$$

In Table A. 8, the rating and the results are presented.

4.2.6.5 POSSIBILITY OF PASSENGER TO CARGO CONVERSION - RE.0005

Conversion means that a product changes its use or functionality without having to be destroyed or recycled. So, instead of being discarded or recycled, the product is given a new 'second life', reducing the need for a new product. The D250-TF is based on the Airbus A320, which has been successfully converted into cargo aircraft (AIRBUS, 2022), a fact that indicates the possibility of converting this configuration to cargo aircraft. On the other hand, the MHEP although of similar size because it uses LH_2 as fuel, the fuel tanks require significant volume limiting the available space. Therefore, a possible conversion for this configuration might not be a viable option for commercial use, as the remaining space is not sufficient for efficient cargo transportation.

4.2.6.6 PRESENCE OF DOCUMENTATION - TRACEABILITY OF USE - RE.0006

This indicator assesses whether a product or component is provided with full documentation that records its history of use throughout its lifespan. Traceability of use describes the ability to monitor the location, the method, and the duration of product or components usages. This information is not available.

4.2.6.7 POSSIBILITY OF DESIGN LIFE EXTENSION - RE.0007

This indicator refers to the ability to extend the life of a product beyond the life for which it was originally designed, through maintenance, upgrading, or redesign of specific components or functions. If there is this possibility, the CE of the product improves. All configurations have defined maintenance tasks, so they all have possibility of design life extension.

4.2.6.8 SAFETY ASSESSMENT OF THE AIRCRAFT - RE.0008

See 4.2.5.3.

4.2.6.9 INTENSITY OF USE OF PRODUCT (COMPARED TO INDUSTRY AVERAGE) - RE.0009

Intensity of use measures how often a product is used, compared to the industry average. The more a product is used, the more value is added to the resources used, so the higher the ration the more circular the product is.

It is calculated as follows:

$$\mathrm{RE.0009} = \frac{lifetime\ of\ the\ configuration}{average\ lifetime\ of\ similar\ products}$$

The average lifetime of similar products is 25 years and the lifetime for all three configurations is 32 years. So, the ratio is the same for all three of them.

4.2.6.10 DESIGN LIFE RE.0010

Designing products that have a long period of life is essential for achieving the CE goals. By extending the life of a product the need for new resources is decreasing. So, the longer the design life is the higher the circularity score is for each option. All configurations have the same design life, which is 32 years (Ramm et al., 2024).

4.2.7 REFURBISH

Refurbish is about restoring a product to a useful condition during expected service life with similar quality and performance characteristics. (International Organization for Standardization., 2024)

4.2.7.1 MAINTENANCE BY USER - RF.0001

Maintenance by user, contributes significantly to enhancing circularity by reducing dependence on external maintenance providers, which leads to savings in resources such as energy, time, and manpower. The convention is that the user is the company that owns the product and the company's specialized staff. There are some maintenance tasks, i.e. A-check, which are performed by airlines themselves, so this indicator would get the value yes across all aircraft.

4.2.7.2 MAINTENANCE BY SPECIALIZED STAFF - RF.0002

When specialized staff performs maintenance, it means that more resources are needed, so it undermines the circularity of the product. External companies perform the majority of the heavy maintenance tasks, so this indicator would get the value yes across all aircraft.

4.2.7.3 PRESENCE OF MAINTENANCE MANUAL - RF.0003

The presence of a maintenance manual facilitates scheduled maintenance. It helps to prevent breakdowns and prolongs the life of the aircraft. The maintenance manual is available for all configurations.

4.2.7.4 POSSIBILITY OF OVERHAUL - RF.0004

See 4.2.5.9.

4.2.7.5 RESOURCES (SUBSTANCES, MATERIALS, TOOLS, ...) FOR MAINTENANCE - RF.0005

See 4.2.5.1

4.2.7.6 PRESENCE OF INSPECTION SCHEDULE - RF.0006

See 4.2.5.6.

4.2.7.7 PERCENTAGE OF AIRCRAFT EQUIPPED WITH SHM SYSTEMS - RF.0007

See 4.2.5.2.

4.2.7.8 RATIO OF MAINTENANCE HOURS AND SERVICE HOURS - RF.0008

The ratio of maintenance hours and service hours is an indicator of the efficiency of use of a product. When more time is spent maintaining a product rather than actively using it, the product is less circular because the goals of CE, regarding the maximization of the value and usage time, are not met.

The data for maintenance hours are provided by (Ramm et al., 2024), and the service hours are calculated in 4.2.2.19.

$$\mathrm{RF.0008} = \frac{\text{mainenance hours}}{RT.0021}$$

4.2.7.9 TIME NEEDED FOR REFURBISHMENT - RF.0009

The more time the refurbishment takes, the longer the aircraft is out of service. When refurbished products are quickly returned to service, the necessity to produce new ones and the consumption of raw materials is reduced. Therefore, the less time required, the more circular the product is. This information is not available because no refurbishment has yet been carried out on these configurations.

4.2.7.10 DURATION OF AVAILABILITY OF REFURBISHMENT - RF.0010

If refurbishment takes too long, it makes the product unavailable for a longer time and it might interfere with other operations, which can be highly costly for the company. This information is not available for the same reason as RF.0009.

4.2.7.11 TIME TAKEN TO DISMANTLE THE PRODUCT (TOTAL) - RF.0011

See 4.2.5.7.

4.2.8 REMANUFACTURE

Remanufacturing is a closed loop process that involves preserving the value-added component of a product so that it can have an added useful lifetime instead of ending up in landfills or recycling.

It is about returning an item, through an industrial process, to a like-new condition from both a quality and performance perspective (International Organization for Standardization., 2024).

4.2.8.1 PRESENCE OF INSPECTION SCHEDULE - RM.0001

A product in order to be remanufacturable needs to retain its structural integrity (ANSI, 2017) and as already mentioned in 4.2.5.6 the inspection schedule contributes in maintaining the product in good condition. So, the presence of the inspection schedule improves the circularity of the product.

4.2.8.2 RESOURCES (SUBSTANCES, MATERIALS, TOOLS, ...) FOR MAINTENANCE - RM.0002

See 4.2.5.1.

4.2.8.3 PERCENTAGE OF COMPONENTS WHICH CAN BE REMANUFACTURED - RM.0003

Apart from the fact that remanufactured components contribute to reducing the need for new materials, they also require far less energy than new ones. This is because remanufacturing reuses components from existing products, reducing the energy needed for material extraction, processing, and manufacturing (MatsumotoDr. & IjomahDr., 2013). Therefore, the higher the percentage of components which can be remanufactured, the more circular the product. The information is not available at this stage.

4.2.8.4 DOCUMENTATION FOR REMANUFACTURE - RM.0004

Keeping track of the technical data and procedures in general ensures transparency and product quality. Documentation for remanufacture includes instructions for disassembly, inspection, cleaning and assembly to ensure the finished product meets the original specifications. It also records which parts have been changed, when and by whom, facilitating defect detection and maintenance. Having documentation for remanufacture improves circularity because it allows the implementation of practices that save resources. This information is not available at this stage.

4.2.8.5 MAINTENANCE BY SPECIALIZED STAFF/USER - RM.0005-0006

See 4.2.7.1, 4.2.7.2.

4.2.8.6 PRESENCE OF MAINTENANCE MANUAL - RM.0007

See 4.2.7.3.

4.2.8.7 POSSIBILITY OF OVERHAUL - RM.0008

See 4.2.5.9.

4.2.8.8 PERCENTAGE OF AIRCRAFT EQUIPPED WITH SHM SYSTEMS - RM.0009

See 4.2.5.2.

4.2.8.9 POSSIBILITY TO UPGRADE - RM.0010

As previously mentioned, every action that will extend the lifespan of the product adds to the circularity. In this case the possibility of product upgrading is an important advantage, as it allows the integration of new technologies without the need to replace the whole product. For example, instead of discarding a system due to technological ageing, only the individual component related to the technology can be replaced, keeping the rest of the product in use which reduces waste. All the configurations have the possibility to upgrade.

4.2.8.10 TIME TAKEN TO DISMANTLE THE PRODUCT (TOTAL) - RM.0011

See 4.2.5.7.

4.2.9 REPURPOSE

Repurpose is the adaptation of a product or its parts to a new function, which is different from the one that this product had before. In the repurpose context, this modification does not require major changes to its chemical of or physical structure(International Organization for Standardization., 2024). It promotes circularity because it gives to a product a different use, reducing waste and the need for new resources allocated to new product production.

4.2.9.1DOCUMENTATION FOR END OF LIFE - PUR.0001

Documentation for end of life includes information from maintenance and component usage records, certificates, aircraft disassembly to critical, recyclable, and hazardous material documentation. Based on this information it is decided what to do with each component, whether it will be given for reuse, landfill, recycling, etc. Without this, aircraft components cannot be reincorporated in the aviation sector, so it plays a vital role in this field. Thus, having it improves circularity.

4.2.9.2 PERCENTAGE OF THE PRODUCT WHICH IS REPURPOSED - PUR.0002

Repurposing gives a second life to a product, thus extending its lifespan. Therefore, the higher the percentage the percentage of the product that can get repurposed the more circular the product is. The information is not available at this stage because the configurations are in a conceptual phase.

4.2.10 CASCADE

Cascade is about "*shift recovered materials from one loop to another to optimize feedstock flows through additional cycles, often with decreasing quality and quantity. When adopting for bio-based material, cascading implies repeated use of renewable resources at decreasing quality, with final treatments such as composting, energy recovery or biodegradation, and safe return of the material to the environment*" (International Organization for Standardization., 2024).

4.2.10.1 PERCENTAGE OF WASTE GENERATED DURING THE MANUFACTURE OF PARTS - CA.0001

Manufacturing waste is an inevitable result of production. Thus, the higher the percentage the less circular the product is. This information is not available at this stage because the data regarding the waste are not available.

4.2.10.2 PERCENTAGE OF THE PRODUCT THAT CAN BE RECYCLED - CA.0002

A high percentage improves the circularity of the aircraft. The percentage of the product that can be recycled is calculated based on the equation below:

$$RC.0001 = \frac{(\sum_{i=1}^{n} m_i * b_i)}{\sum_{i=1}^{n} m_i} \qquad [\%]$$

m_i is the mass of each material of each module of each aircraft;

b_i is the percentage of the mass of the i material, which is allocated for recycling;

n is the total number of materials for all the modules of each aircraft.

The results are presented in Table A. 9 and Table A. 10.

4.2.10.3 USE OF AIRCRAFT MATERIALS FOR OTHER PURPOSES - CA.0003

As already mentioned, using aircraft materials, to other systems, for example using the aircraft insulation for the building sector improves the circularity because it limits the need for new resources. This information is not available at this stage because there is not sufficient information about this.

4.2.11 RECYCLE

"Recycle is returning materials to the production loop with the higher or lower quality. It includes activities such as recovery, collection, transport, sorting cleaning and reprocessing" (International Organization for Standardization., 2024).

4.2.11.1 PERCENTAGE OF THE PRODUCT THAT CAN BE RECYCLED RC.0001

See 4.2.10.2.

4.2.11.2 PERCENTAGE OF MATERIALS RECOVERED THROUGH RECYCLING PROCESSES RC.0002

A high percentage improves the circularity of the aircraft. The percentage of materials recovered through recycling processes is calculated based on the equation below:

$$RC.0002 = \frac{(\sum_{i=1}^{n} m_i * b_i * a_i)}{\sum_{i=1}^{n} m_i} \qquad [\%]$$

m_i is the mass of each material of each module of each aircraft;

b_i is the percentage of the mass of the i material, which is allocated for recycling;

a_i is percentage at which each recyclable mass m_i is recycled;

n is the total number of materials for all the modules of each aircraft.

The results are presented in Table A. 9 and Table A. 10.

4.2.11.3 DOCUMENTATION FOR END OF LIFE RC.0003

See 4.2.9.1.

4.2.11.4 END OF LIFE PROCESS FOR EVENTUAL UNAVOIDABLE HAZARDOUS MATERIALS RC.0004

Hazardous materials include substances that can cause serious harm to both human health and the environment. In the context of a CE, it is crucial that materials and components remain in use for as long as possible to reduce the need for primary resources and waste production. Because the demand for recycled materials is growing, it is important to ensure that those containing hazardous substances are treated safely and in accordance with the regulations. For this reason, it is important to have a clear framework for end-of-life treatment to avoid the release of toxic substances into the environment during collection, dismantling, recycling, and disposal.

4.2.12 RECOVER ENERGY

Generate useful energy from resources diverted from waste disposal, like non-recyclable materials (International Organization for Standardization., 2024).

4.2.12.1 PERCENTAGE TO INCINERATION EN.0001

Incineration is a waste disposal method where the waste is combusted. When waste is burned, the raw materials and energy invested in its production are lost, so when the higher percentage of incineration, the less circular the product. This indicator is calculated as follows:

$$EN.0001 = \frac{(\sum_{i=1}^{n} m_i * c_i)}{\sum_{i=1}^{n} m_i} \qquad [\%]$$

m_i is the mass of each material of each module of each aircraft;

c_i is the percentage of the mass of a specific material, for the corresponding structure, which is incinerated;

n is the total number of materials for all the modules of each aircraft.

The results are presented in Table A. 9 and Table A. 10.

4.2.12.2 PERCENTAGE OF WASTE GENERATED DURING THE MANUFACTURE OF PARTS EN.0002

See 4.2.10.1.

4.2.12.3 DOCUMENTATION FOR END OF LIFE EN.0003

See 4.2.9.1.

4.2.12.4 END OF LIFE PROCESS FOR EVENTUAL UNAVOIDABLE HAZARDOUS MATERIALS EN.0004

See 4.2.12.4.

4.2.13 RE-MINE

"*Mining or extraction from landfills and waste plants can be possible in some cases if the related activities are sustainably managed*" (International Organization for Standardization., 2024).

4.2.13.1 DOCUMENTATION FOR END OF LIFE MI.0001

See 4.2.9.1

4.2.13.2 PERCENTAGE OF THE PRODUCT THAT GOES TO LANDFILL MI.0002

Landfill is a site where products/components that cannot get reused or recycled are discarded. When a product ends up in landfill, valuable natural resources like minerals, energy, and water, that were used to produce them are lost, which undermines the CE principles. Therefore, the higher the percentage, the less circular the aircraft. This indicator is calculated as follows:

$$MI.0002 = \frac{(\sum_{i=1}^{n} m_i * d_i)}{\sum_{i=1}^{n} m_i} \qquad [\%]$$

m_i is the mass of each material of each module of each aircraft;

d_i is the percentage of the mass of the i material, for the corresponding structure, which goes to landfill;

n is the total number of materials for all the modules of each aircraft.

The results are presented in Table A. 9 and Table A. 10.

4.2.13.3 PERCENTAGE OF WASTE GENERATED DURING THE MANUFACTURE OF PARTS MI.0003

See 4.2.10.1.

4.2.13.4 END OF LIFE PROCESS FOR EVENTUAL UNAVOIDABLE HAZARDOUS MATERIALS MI.0004

See 4.2.12.4.

4.2.13.5 ENERGY RECOVERED VIA INCINERATION MI.0005

Recovering energy via incineration is the energy produced by the combustion of waste and the utilization of it for reuse. Energy recovery through incineration is important for waste management, especially when other actions like reuse or recycling is not possible. It is a way to retain resources, in this case in another form, in use for as long as possible. So, the more energy recovered from the incineration of one product the more circular the product is. This indicator is calculated based on the equation bellow:

$$MI.0005 = \sum_{i=1}^{n} \frac{(m_i * c_i * e_i)}{100} \qquad [MJ]$$

m_i is the mass of each material of each module of each aircraft;

c_i is the percentage of the mass of a specific material, for the corresponding structure, which is incinerated;

e_i is the energy released during the incineration of one kilogram of material (i), measured in Megajoules per kilogram;

n is the total number of materials for all the modules of each aircraft.

The results are presented in Table A. 9 and Table A. 10, in Appendix A.

5.0 IMPLEMENTATION OF CHAPTER 3 TO CHAPTER 4

This thesis follows a quantitative approach to the CE assessment of three aircraft configurations, see Chapter 3.1.2. The methodology includes the adaptation of an existing list of CE indicators, the collection of data from heterogeneous sources, the evaluation of those values, the application of utility functions to convert the numerical values of the indicators into comparable scores in order to reduce subjectivity and uncertainty in the assessment.

The initial list of CE indicators was based on the work of (Ligeia, 2025) which addresses the assessment of the CE at the component level. From this list, as many indicators as could be applied at the aircraft level, they were selected and adapted. The final indicators were organized into thirteen RMA, according to ISO 59004:2024 standard for CE assessment and are the ones presented in Chapter 4.

To better explain the application of chapter 3 use cases to chapter 4 indicators, the indicator “Percentage of recyclable materials” will be used It is expressed in percentage (%) points and is part of the Reduce RMA.

5.1 DATA COLLECTION

All data derives from three sources:

- DLR-EXACT internal files (CPACS-files),
- DLR internal files (Excel-files),
- Documented cases, where there were deficiencies,

For some indicators, it has not been possible to obtain numerical values, and such cases have been omitted from the final assessment.

For the indicator illustrated, the data has been downloaded by DLR internal files. Please refer to chapter 4.2.3.3 for extensive information on the aforementioned indicator calculation. The values for each configuration are presented in Table 9. Also, in this step the range for each indicator has been defined. In this example, since it was a percentage variable, the range goes from 0 to 100.

Table 9: Example of data collection for RD.0013 indicator

Indicator	Unique Identifier	Unit	Range from	Range to	D250-TF- FF	D250 -TF-SF	D250-TFLH2-MHEP
Percentage of recyclable materials	RD.0013	%	0	100	81.66	81.66	62.77

5.2 INDICATOR EVALUATION

The evaluation of the indicators has been carried out in two stages. First, each indicator was rated on a scale from 1 to 5, where 1 corresponds to the least circular option and 5 to the most circular one. This initial evaluation has been based on literature data, technical reports, and the empirical judgement of the researcher. The aim was to assign comparable scores to heterogeneous indicators, so as to ensure consistency and comparability when processing the results. The scores that resulted from the initial evaluation will be called initial scores in the context of this thesis.

However, in order to limit the subjectivity that was introduced by the initial evaluation, a utility function has been calculated for each indicator based on the initial scores. Such process is meant to produce new, standardized utility values based on the correlation of the numerical values of the indicators with their respective initial scores. In particular, this approach draws inspiration from the Multi-attribute Utility Theory (MAUT), without fully applying its theoretical background, but utilizing its basic principle: the conversion of objective values into comparable units of preference, so as to support decision-making (Donelli, 2024). More specifically, for each indicator the numerical values and the initial scores for the three configurations were collected. These points were used to train a linear regression, which also included predefined anchors representing ideal (score 5) and undesirable (score 1) values of the indicator. Based on the resulting trend, the predicted scores for each configuration were calculated. In contrast to a simple conversion of numerical values based on fixed thresholds, this method allowed for dynamic derivation of values based on the behavior of the data as reflected in the initial evaluation. The MATLAB environment has been used to run this simulation. The scores that resulted from the utility function will be called utility scores in the context of this thesis.

For the RD.0013 indicator, the initial evaluation is as follows:

Values between 80-100 % : score 4

Values between 40-80 % : score 3

Values between 0-40 % : score 2

Therefore, the initial rating has been formed as follows, Table 10:

Table 10: Example of initial rating for RD.0013 indicator

	D250-TF- FF	D250-TF- SF	D250-TFLH2-MHEP
Initial rating	4	4	3

For the utility scores, the following process applied:

First, two anchors were defined. The anchor values were set at 0% and 100%. These values in turn have been assigned a rating of 1 to 5, respectively. Linear regression has been then applied to the anchors as well as to the initial scores of the configurations. The final utility score for each configuration has been calculated, as shown in Table 11.

Table 11: Example of utility scores for RD.0013 indicator

	D250-TF- FF	D250-TF- SF	D250-TFLH2-MHEP

Predicted score	4.04	4.04	3.31

The process of transforming the initial scores into utility scores is illustrated in Figure 17. The latter shows:

- the initial values and scores of the three configurations (Original Data),
- the anchors at the ends of the scale
- the linear regression line resulting from all points (Linear trend)
- the final utility scores for each configuration (predicted points)

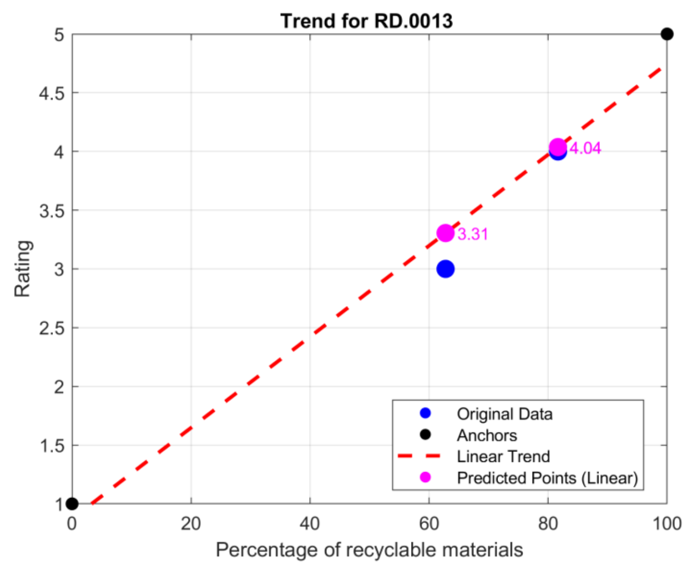

Figure 17: Visualization of the conversion of initial values of the RD.0013 into utility scores (1-5), using linear regression between actual values and reference points.

5.3 DEFINITION OF INDICATOR IMPORTANCE

Following the indicator evaluation has been the definition and implementation of an importance weight to determine the relative importance of each indicator within the RMA to which it belongs. The degree of importance rates from 1 to 9, where 9 corresponds to highest importance values. The importance assignment is based on the contribution of each indicator to its corresponding RMA. These weights do not vary between the three configurations. In contrast, they remain constant across them, to maintain the comparability of results and avoid bias.

The RD.0013 indicator belongs to the Reduce RMA (see 4.2.4) hence the importance factor will be calculated on the basis of how important this indicator is for this specific RMA. In general, the Reduce RMA aims to decrease the amount of resources. However, when the percentage of recyclable materials used in a product is high, the RD.0013 indicator -does not directly reduce resource consumption, but rather ensures that these materials can be recycled and reused in the future, thus reducing the need for new raw materials. This is why the RD.0013 indicator has been assigned an average importance rating, $w_i = 5$, as it is necessary but not critical in the resource reduction strategy.

5.4 RMA SCORES CALCULATION

After the assignment of the importance weight, the calculation of the RMA scores is next in line. In total four scores have been calculated for each RMA in each configuration, resulting in:

1. The average of the initial scores;
2. The weighted average of the initial scores, based on the importance weights of the individual indicators;
3. The average of the utility scores;
4. The weighted average of the utility scores, based on the importance weights of the individual indicators.

Bellow the equations for each RMA score are presented. The RMA scores are calculated separately for each configuration.

1. Average of initial scores

   $RMA\ score_1$ is the average of the initial ratings for each indicator and is calculated based on the equation:

$$RMA\ score_1 = \frac{1}{n}\sum_{i=1}^{n} r_i$$

   Where:

   - r_i: initial rating for indicator i;
   - n: number of parameters in the RMA.

2. Average of initial scores with importance weight

   When the importance weight of each indicator is taken into account, $RMA\ score_2$ is weighted average of the initial ratings and is calculated based on:

$$RMA\ score_2 = \frac{\sum_{i=1}^{n} r_i * w_i}{\sum_{i=1}^{n} w_i}$$

   Where:

   - w_i: Importance weight of parameter i;

3. Average of utility scores

   $RMA\ score_3$ is the average of the utility scores for each indicator and is calculated based on the equation:

$$RMA\ score_3 = \frac{1}{n}\sum_{i=1}^{n} u_i$$

Where:

u_i: the score of the parameter i obtained from the utility function;

4. Average of utility scores with importance weight

   When the importance weight of each indicator is taken into account, $RMA\ score_4$ is weighted average of the utility scores and is calculated based on:

$$RMA\ score_4 = \frac{\sum_{i=1}^{n} u_i * w_i}{\sum_{i=1}^{n} w_i}$$

5.5 CIRCULARITY SCORES

The circularity scores for each configuration are calculated using the RMA scores. In order to derive the overall circularity score per configuration, three different weight cases were applied reflecting different priorities.

- Case 1: All RMAs have equal weight;
- Case 2: Design focused RMAs were each assigned double the weight compared the others;
- Case 3:EoL focused RMAs were each assigned double the weight compared the others.

  The circularity scores are calculated based on the equation:

$$CS_1 = \frac{\sum_{j=1}^{k} (RMA\ score_m)_j * b_j}{\sum_{j=1}^{k} b_j}$$

Where:

m: the RMA score used (1 out of 4);

k: number of RMAs;

b_j: the weight of the j RMA based on the case.

In Table 12 the weights for each Case/RMA are presented.

Table 12: Weighting of the 13 RMAs for each Case

RMA	Case 1	Case 2	Case 3
Refuse	0.077	0.118	0.056
Rethink	0.077	0.118	0.056

Circular Sourcing	0.077	0.118	0.056
Reduce	0.077	0.118	0.056
Repair	0.077	0.059	0.056
Re-use	0.077	0.059	0.056
Refurbish	0.077	0.059	0.056
Remanufacture	0.077	0.059	0.056
Repurpose	0.077	0.059	0.111
Cascade	0.077	0.059	0.111
Recycle	0.077	0.059	0.111
Recover Energy	0.077	0.059	0.111
Re-mine	0.076	0.059	0.111

6.0 RESULTS

In this section, the results of the assessment are presented following the methodology outlined in Chapter 5. Before analyzing in greater detail the results, it is important to mention again that the distribution of indicators among the 13 RMAs, as shown in Figure 15, varies significantly. Some RMAs include a large number of indicators (e.g., Rethink), while others include fewer (e.g. Cascade).

In addition, the degree of data availability for each RMA varies to a great extent. Figure 18 shows the availability of numerical values per indicator and RMA. It is observed that, even when indicators have been defined, data are not always available, resulting in their exclusion from the final assessment. Some RMAs have zero data availability for all their indicators and therefore do not contribute at all to the calculation of the final score.

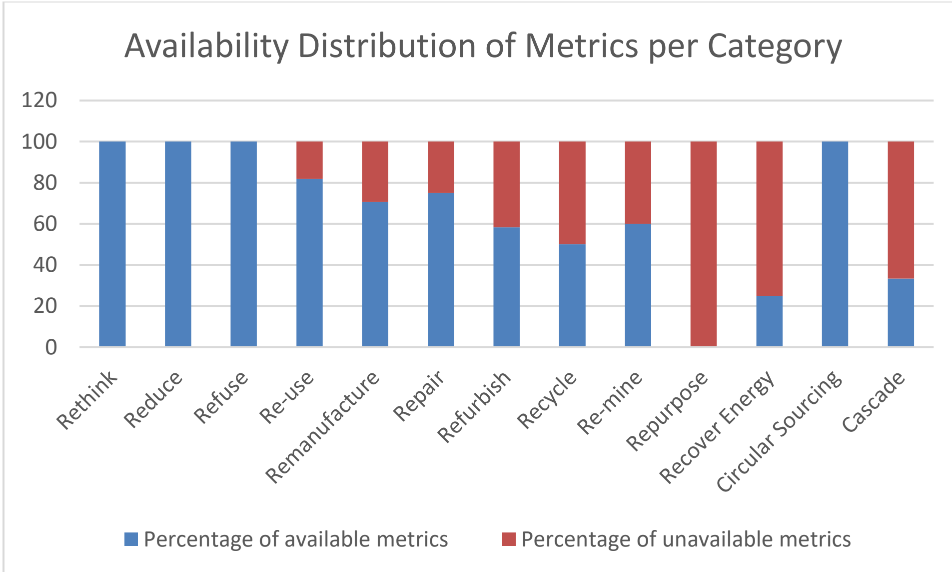

Figure 18: Availability of indicators per category

These inconsistences and differences explain why the application of different weighting scenarios has had a different impact on the results. RMAs that had increased weighting but limited information completeness, as in Case 3, affect the final score less compared to groups in Case 2, for which there was a large availability of data.

The final circularity scores are presented in Table 13.

Table 13: Final circularity scores

Case	Rating (1-5), 5: most circular						Utility function rating (1-5), 5: most circular					
	without importance			with importance			without importance			with importance		
	D250-TF- F	D250-TF-SF	D250-TFLH2-MHEP	D250-TF- F	D250-TF-SF	D250-TFLH2-MHEP	D250-TF- F	D250-TF-SF	D250-TFLH2-MHEP	D250-TF- F	D250-TF-SF	D250-TFLH2-MHEP
1	2.68	2.81	2.97	2.73	2.92	3.08	2.69	2.82	2.82	2.74	2.88	2.88
2	2.58	2.78	2.98	2.60	2.60	3.10	2.59	2.78	2.87	2.61	2.83	2.90
3	2.62	2.71	2.98	2.65	2.80	3.06	2.69	2.73	2.76	2.68	2.78	2.80

Summarizing, it is observed that the final result of the evaluation is influenced by the calculation method, the use of importance factors, as well as by the degree of data availability in each RMA.

Case 2 led to stronger differentiations between the configurations, due to the participation of a large number of indicators with complete data, while in Case 3 similar scores for all configurations were observed, due to the incomplete coverage of the corresponding parameters.

The pie chart, Figure 19, shows, in a percentage distribution form, how the three aircraft configurations were ranked in terms of CE. Each aircraft was assessed in three separate cases. Four distinct categories of criteria were applied to each case (Initial rating with and without importance weight and Utility function rating with and without importance weight), resulting in twelve individual numerical values per aircraft. The higher the value, the more circular the aircraft is considered to be. Then, within each sub-combination of case-category criteria, the three configurations were ranked first, second or third according to their relative scores.

The chart shows the percentage of times each configuration was ranked first (gold section), second (silver) or third (bronze) in just these individual rankings. Thus, 91.7 % of the gold section for the D250-TFLH2-MHEP means that in eleven of the twelve evaluation conditions this aircraft scored the highest value, while the corresponding 91.7 % of the bronze section for the D250-TF-FF indicates that it was found third in eleven of the twelve conditions and the 91.7 % of the silver section for the D250-TF-SF indicates that it was found second in eleven of the twelve conditions. In this way, the graph provides a compact visual summary of the consistency with which each configuration excelled or lagged across all cases and criteria, facilitating an understanding of their overall performance.

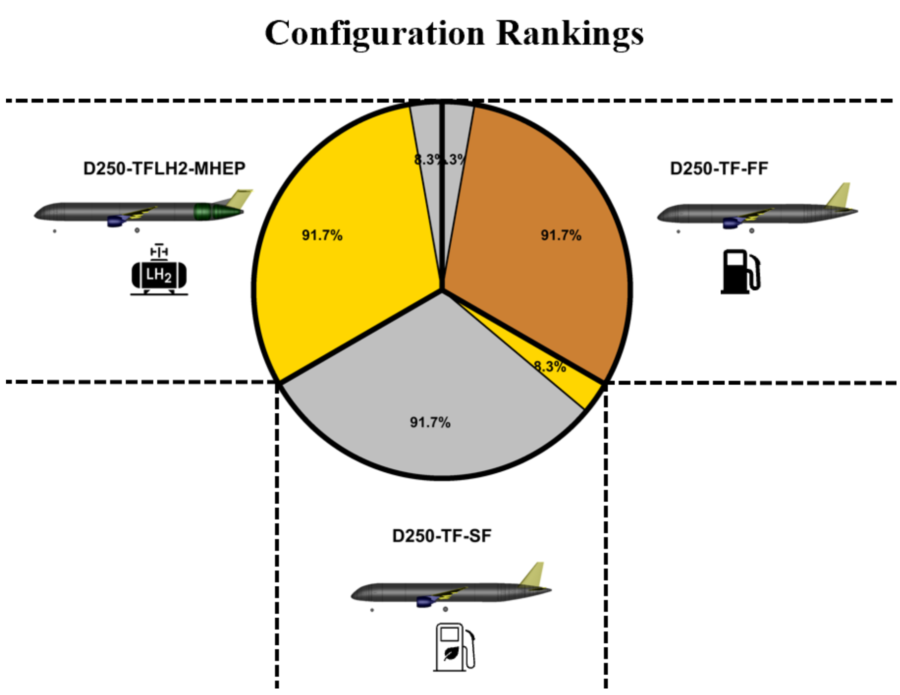

Figure 19: Configuration Rankings Pie chart. Percentage distribution of the positions (1st-gold, 2nd-silver, 3rd-bronze) occupied by the three aircraft configurations D250-TFLH2-MHEP, D250-TF-SF and D250-TF-FF in 12 combinations of CE assessment (3 cases × 4 evaluation categories). The intersections of the circle show the frequency with which each configuration was ranked first, second or third in terms of relative CE score.

The graphs that follow depict the circularity scores of the three aircraft configurations for the three weighting scenarios considered.

6.1 CASE 1 – EQUAL WEIGHTING

In the first scenario, where all RMAs have equal weighting, D250-TFLH2-MHEP consistently displays the highest circularity scores, regardless of the evaluation method. The application of importance factors further strengthens the difference between D250-TFLH2-MHEP and the other two aircraft. Additionally, it is observed that the scores obtained through the utility function where slightly lower than the corresponding initial ones, which is due to the smoothing of subjective assessments. However, the relative ranking among the aircraft configurations remains stable. These results are outlined in Figure 20.

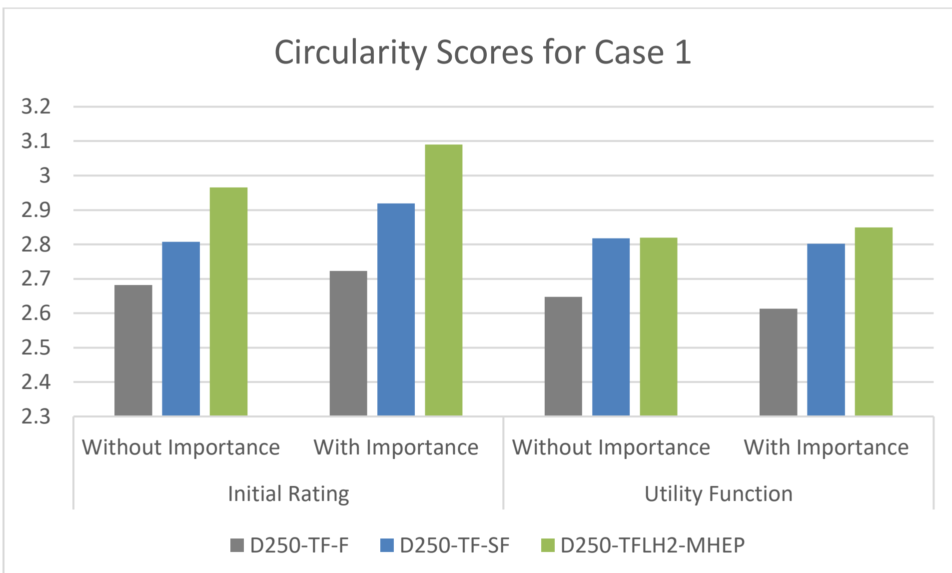

Figure 20: Final circularity scores for Case 1

In order to better understand the way that these scores have been calculated, three stack bars are presented further down, in Figure 21. These represent the initial rating and the process of calculating the circularity score for the D250-TFLH2-MHEP in case 1. The first column (Total with green) shows the value of the aircraft's circularity score. The second column (RMAs) breaks this value down into 13 individual Resource Management Actions (RMAs), such as Refuse, Reuse, Remanufacture, etc. Each RMA is represented by a different color, and the height of each segment indicates the contribution of each RMA to the overall score. All RMAs have the same weight for Case 1, in the composition of the cyclicality score. Therefore, the differences in the height of the segments in the second column reflect the relative score of each RMA and not differences in their importance or priority in the overall model. The third column captures how the score of each RMA is derived, presenting in the individual evaluation indicators associated with each RMA. These indicators are assigned with shades of the corresponding color of their group, and their total height is equal to the height of the corresponding RMA in the middle column.

It is observed that some RMAs, such as Rethink or Reduce, are calculated based on several individual indicators, resulting in a more multidimensional assessment. On the other hand, other RMAs, such as Cascade or Recover Energy, are based on only one indicator, while RMA Repurpose does not contribute at all to the overall score, due to lack of available data.

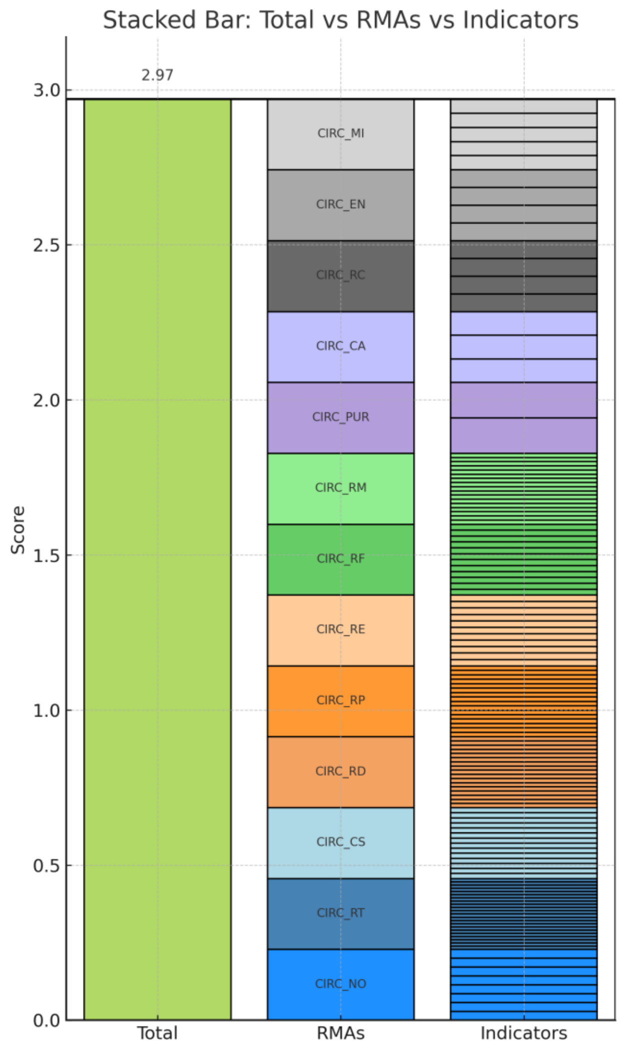

Figure 21: Visual representation of the circularity score decomposition. The left bar shows the total circularity score of the MHEP (Initial Rating w/o importance weight). The middle bar breaks this total down into 13 RMAs, each represented by a distinct color. The right bar further decomposes each RMA into its indicators, shown as stacked pieces in matching color tones. All three bars are normalized to the same total height.

6.2 CASE 2 – DESIGN RMA FOCUSED

When more weight is assigned to the design related RMAs, the D250-TFLH2-MHEP still displays the highest scores, although by a smaller margin, compared to the Figure 20. In the case of initial scores with importance weights, it is observed that D250-TF-SF approaches the scores of D250-TFLH2-MHEP, while the differences between them are significantly limited. In the values obtained through the utility function, the general ranking remains consistent.

More specifically, in Case 2, the increased weighting has been applied to four RMAs (Refuse, Rethink, Circular Sourcing and Reduce), which included 8, 22, 14 and 12 indicators, respectively. For all 58 total indicators in these groups, data were available across all aircraft configurations, which made these specific RMAs to the final score significant.

The application of weights works in favor of D250-TF-SF, which approaches the performance of D250-TFLH2-MHEP. The above observations are presented in Figure 22.

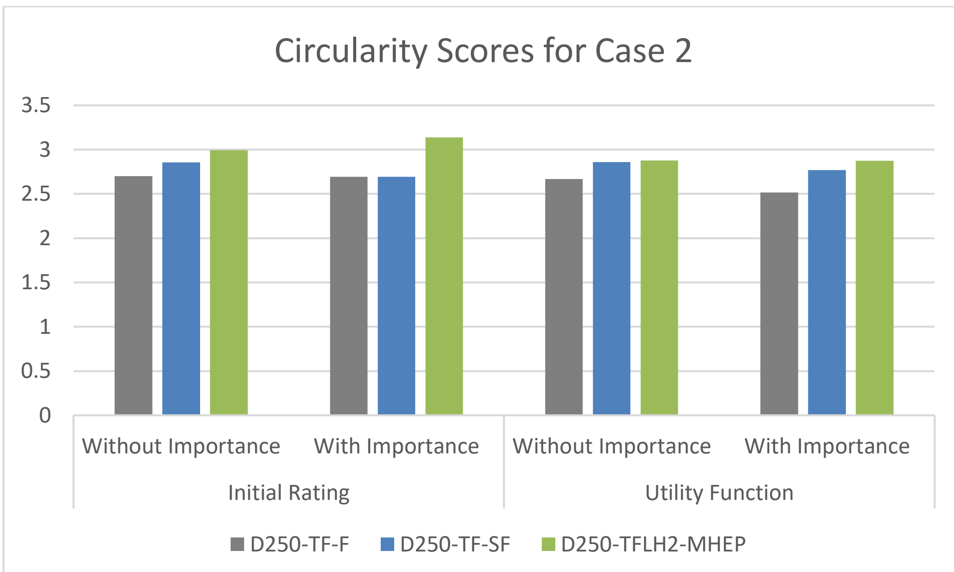

Figure 22: Final circularity scores for Case 2

These results are expected, because these RMAs include indicators like: presence of electric taxiing, percentage that follows the Ecodesign principles, the LCA results, type of fuel and propulsion type, where in these the D250-TFLH2-MHEP aircraft is significantly outperformed. In the majority of the other metrics in these RMAs, the three aircraft show similar values.

6.3 CASE 3 – EOL RMA FOCUSED

In the third scenario, where more weight is given to RMAs related to EoL, the differences between configurations are significantly reduced. All configurations represent similar scores, mainly in the utility function assessments. This relates to the scarcity or absence of quantifiable indicators in many of these RMAs which essentially means that the increased RMA weight has less substantial impact on the final score.

More specifically, in Case 3, the increased weighting has been applied to six RMAs, namely Repurpose, Cascade, Recycle, Recover Energy and Remine, each of them including a specific number of indicators and in particular 2, 3, 4, 4 and 5 indicators respectively. However, data availability has been limited across these RMAs:

- Repurpose did not have any indicator with an available value out of 2.
- Cascade had only 1 indicator available out of 3.
- Recycle had 2 out of 4.
- Recover Energy had 1 out of 4.
- Remine had 3 out of 5.

In total, only 7 out of 18 indicators from these groups were finally included in the evaluation. Therefore, the fact that these scores are so close, especially for those resulting from the utility function scores which are almost the same, can therefore be assigned both to the fact that all three configurations might not differentiate that much in these RMAs and to the low number of indicators that were used. Furthermore, these RMAs contain mainly indicators about the components of the aircraft, their materials and more specifically whether they are recyclable, recycled, whether they end up in landfill or in incineration. Since the aircraft under consideration do not have very big differences in their materials and in the weight of their frames, there are no big changes in the scores determined by these indicators and the changes observed are mainly due to the small contribution of the other groups. The above observations are depicted in Figure 23.

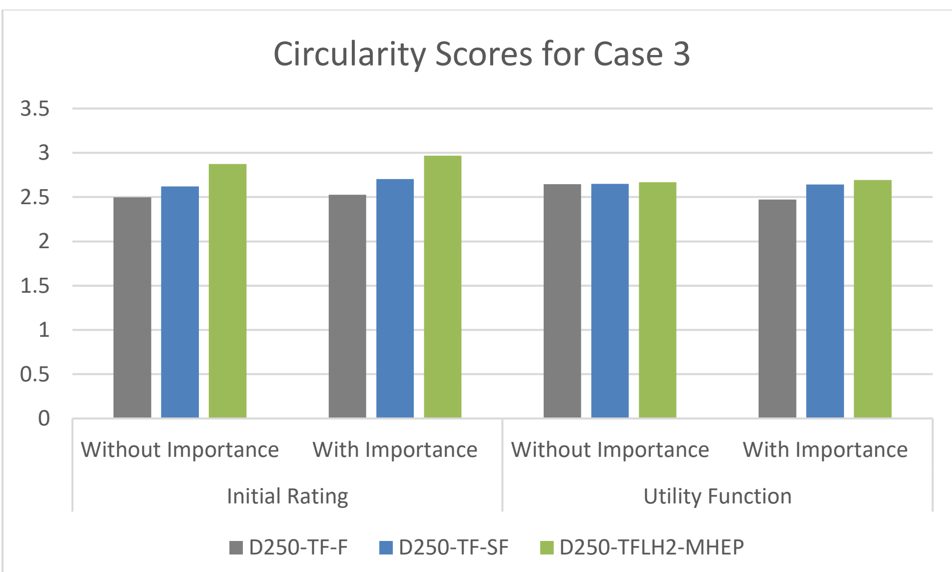

Figure 23: Final circularity scores for Case 3

7.0 CONCLUSION AND RECOMMENDATIONS

7.1 SUMMARY OF FINDINGS

In this thesis a framework for assessing the CE of three aircraft configurations has been applied. Based on the proposed methodology, scores were developed through an initial qualitative assessment, but also through utility functions, in order to reduce subjectivity and increase comparability between heterogeneous data. For the final assessment three different weighting scenarios were applied.

The results of the different weighting scenarios lead to the following main conclusions:

- The relative ranking of the aircraft remained consistent, with D250-TFLH2-MHEP showing the highest circularity score and D250-TF-F the lowest. D250-TF-SF presented intermediate performances, with small fluctuations depending on the calculation method.
- The application of importance factors highlighted differences in the scores, enhancing the influence of the indicators with greater CE importance. D250-TF-F, for example, was more negatively affected when the weight of the indicators was taken into account.
- The use of the utility function limited the extreme deviations and offered a more neutral and stable representation of the scores. However, the main trends of the results were maintained.
- The influence of the weighting scenarios varied depending on the completeness of the data per RMA. In Case 2, the RMAs that received increased weight had many indicators and were well documented, resulting in the weighting having a substantial influence. In contrast, in Case 3, the absence of data on many indicators of the RMA limited the effectiveness of the weighting.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The implementation of this assessment framework has highlighted both its potential and limitations, mainly related to the availability and definition of indicator. The following directions for future research are suggested:

1. Data availability

One of the main difficulties of this study was the quantification of a large proportion of the indicators defined in the methodology. When the value of an indicator could not be calculated of found, this specific indicator was excluded from the final evaluation, resulting in reduced depth and accuracy of the analysis. For example, in the repurpose RMA, none of the available indicators had values, and therefore was not included at all in the final assessment. Thus, in future work, it is suggested to focus on the completeness of data for each selected indicator.

2. Define the same number of indicators for each RMAs

This study has had significant variability in the number of indicators included per RMA, some RMAs had 20 indicators while some others 2. This asymmetry affects the equivalent representation of the RMAs in the final evaluation. Thus, it is recommended to further investigate and introduce additional indicators in those underrepresented RMAs, so that there will be a greater balance in the framework structure.

3. Extending the methodology to more aircraft configuration scenarios

The assessment was applied to three aircraft configurations. In order to enhance the reliability of the conclusions and generalize the method, it would be useful to apply the methodology to a wider range of aircraft configurations.

4. Assumptions

It is important to note that results do not only rely on the data, but they also depend on the assumptions behind those values. Those include ongoing aviation practices, regulatory restrictions and technical constraints - such as the use of hazardous materials in coatings or the fact that composites cannot yet be recycled at least at an industrial scale. These assumptions mainly made for the configuration that uses LH_2 reflect the reality of today's aircraft in operation but do not represent the full capabilities of future technologies, like the incorporation of fuel cell systems as a secondary power unit in aircraft, which will need to be taken into consideration in long-term CE assessments.

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APPENDICES A

A.1 SUPPLEMENTARY FIGURES AND TABLES

Table A. 1: Number of sub-modules for the D250-TFLH2 and D250-TF

Sub-modules		
	D250-TFLH2-MHEP	**D250-TF**
Structure	Wing	Wing
	HTP	HTP
	VTP	VTP
	Fuselage	Fuselage
	Landing Gear	Landing Gear
	Pylon	Pylon
Power Unit	Nacelle	Nacelle
	Engine Systems	Engine Systems
	Gearbox	Gearbox
	Gas Turbine	Gas Turbine
	Fan	Fan
Systems	Auxiliary Power Unit	Auxiliary Power Unit
	Hydraulic Systems	Hydraulic Systems
	Air Conditioning	Air Conditioning
	Deicing	Deicing
	Fire Protection	Fire Protection

	Flight Controls	Flight Controls
	Instrument Panel	Instrument Panel
	Automatic Flight System	Automatic Flight System
	Communication	Communication
	Electrical Systems	Electrical Systems
	Navigation	Navigation
	LH2 Tank System	-
	LH2 Tank Structure	-
	Installation	-
	Thermal Management	-
	Cables	-
	Ass Idle	-
	E-Taxi System	-
	Power Electronics	-
	Fuel Cell Stack	-
	Fuel Cell Subsystems	-
Furnishing	Furnishing	Furnishing
Operator Items	Operator Items	Furnishing
RD.0004	**34**	**24**

Table A. 2: RT0001 and RT0002 calculation and values

		RT.0001		RT.0002	
Modules	Submodules	D250-TF	D250-TFLH2-MHEP	D250-TF	D250-TFLH2-MHEP

Structure	Wing	0	0	1	1
	HTP	0	0	1	1
	VTP	0	0	1	1
	Fuselage	0	0	1	1
	Landing Gear	1	1	0	0
	Pylon	0	0	1	1
Power Unit	Nacelle	0	0	1	1
	Engine Systems	1	1	0	0
	Gearbox	1	1	0	0
	Gas Turbine	1	1	0	0
	Fan	1	1	0	0
Systems	Auxillary Power Unit	1	1	0	0
	Hydraulic Systems	0	0	1	1
	Air Conditioning	0	0	1	1
	DeIcing	0	0	1	1
	Fire Protection	0	0	1	1
	Flight Controls	0	0	1	1
	Instrument Panel	0	0	1	1
	Automatic Flight System	0	0	1	1
	Communication	0	0	1	1
	Electrical Systems	0	0	1	1
	Navigation	0	0	1	1
	LH2 Tank System		0		1

	LH2 Tank Structure		0		1
	Installation		0		1
	Thermal Management		0		1
	Cables		0		1
	Ass Idle		0		1
	E-Taxi System		0		1
	Power Electronics		0		1
	Fuel Cell Stack		0		1
	Fuel Cell Subsystems		0		1
Furnishing	Furnishing	1	1	0	0
Operator Items	Operator Items	1	1	0	0
Results		**33.33**	**23.53**	**72.73**	**76.47**

Table A. 3: Percentage of the product which can be disassembled

		RP.0019	
Modules	Submodules	D250-TF	D250-TFLH2-MHEP
Structure	Wing	1	1
	HTP	1	1
	VTP	1	1
	Fuselage	0	0
	Landing Gear	1	1
	Pylon	1	1
Power Unit	Nacelle	1	1

	Engine Systems	1	1
	Gearbox	1	1
	Gas Turbine	1	1
	Fan	1	1
Systems	Auxillary Power Unit	1	1
	Hydraulic Systems	1	1
	Air Conditioning	1	1
	DeIcing	1	1
	Fire Protection	1	1
	Flight Controls	1	1
	Instrument Panel	1	1
	Automatic Flight System	1	1
	Communication	1	1
	Electrical Systems	1	1
	Navigation	1	1
	LH2 Tank System	0	1
	LH2 Tank Structure	0	1
	Installation	0	1
	Thermal Management	0	1
	Cables	0	1
	Ass Idle	0	1
	E-Taxi System	0	1
	Power Electronics	0	1
	Fuel Cell Stack	0	1
	Fuel Cell Subsystems	0	1
Furnishing	Furnishing	1	1
Operator Items	Operator Items	1	1

Results	**95.83**	**94.29**

Table A. 4: Material information for D250-TF-FF and D250-TF-SF

A	B	C	D	E	F	G	H	I
D250-TF	**Weight(kg)**	**Recyclability**	**Critical materials**	**Hazardous material/ chemical content during processing**	**Percentage of the materials that are recyclable**	**Percentage of the materials that are critical**	**Percentage of the critical materials that are recyclable**	**Percentage of hazardous material/chemical content during processing**
CFRP	2521.03	0	0	1	0.00	0.00	0.00	6.97
AL 2024	18756.49	1	1	1	51.84	51.84	63.48	51.84
High-Strength Steel	5087.27	1	1	1	14.06	14.06	17.22	14.06
Ti64	2521.03	1	1	0	6.97	6.97	8.53	0.00
Ni-Superalloy	2129.86	1	1	0	5.89	5.89	7.21	0.00
Copper	1051.60	1	1	0	2.91	2.91	3.56	0.00
Polypropylene	2521.03	0	0	0	0.00	0.00	0.00	0.00
Polyester Fiber	1592.48	0	0	0	0.00	0.00	0.00	0.00
RD.0011: 8					**81.66**	**81.66**	**100.00**	**72.87**

Table A. 5: Material information for D250-TFLH2 -MHEP

A	B	C	D	E	F	G	H	I
D250-TFLH2 - MHEP	**Weight (kg)**	**Recyclability**	**Critical materials**	**hazardous material/ chemical content during processing**	**Percentage of the materials that are recyclable**	**Percentage of the materials that are critical**	**Percentage of the critical materials that are recyclable**	**Percentage of hazardous material/ chemical content during processing**
CFRP	15307.04	0	0	1	0.00	0.00	0.00	28.05
AL 2024	22983.61	1	1	1	42.11	42.11	67.12	42.11

High-Strength Steel	5714.70	1	1	1	10.47	10.47	16.69	10.47
Ti64	2049.82	1	1	0	3.76	3.76	5.99	0.00
Ni-Superalloy	2229.19	1	1	0	4.08	4.08	6.51	0.00
Copper	1081.16	1	1	0	1.98	1.98	3.16	0.00
Polypropylene	3136.78	0	0	0	0.00	0.00	0.00	0.00
Polyester Fiber	1755.09	0	0	0	0.00	0.00	0.00	0.00
Platinum	0.22	1	1	0	0.00	0.00	0.00	0.00
Carbon black	3.04	0	0	0	0.00	0.00	0.00	0.00
Tetrafluoroethylene	5.24	0	1	1	0.00	0.01	0.00	0.01
carbon fiber	15.41	0	0	0	0.00	0.00	0.00	0.00
Weaving cotton	15.41	1	0	0	0.03	0.00	0.00	0.00
Graphite	173.32	1	1	0	0.32	0.32	0.51	0.00
Thermoset Plastic	74.28	0	0	0	0.00	0.00	0.00	0.00
Glass Fiber (end plate)	3.30	0	0	0	0.00	0.00	0.00	0.00
Epoxy (end plate)	3.30	0	0	0	0.00	0.00	0.00	0.00
Copper (collector)	6.05	1	1	0	0.01	0.01	0.02	0.00
Chromium steel	3.85	1	0	1	0.01	0.00	0.00	0.01
Polypropylene (casing)	16.51	0	0	0	0.00	0.00	0.00	0.00
RD.0011: 20					**62.77**	**62.74**	**99.98**	**80.65**

Table A. 6: Total energy necessary for manufacturing for D250-TF

D250-TF				
Module	**Material***	**Mass [kg]**	**Amount [kWh]**	**RD0004**
Structure	CFRP	9253.61	11.15	103224

	AL 2024	12636.13	10.62	134195.7
	High-Strength Steel	2710.19	4.82	13073.96
	Ti64	913.24	5.53	5050.22
Power Unit	CFRP	1646.24	11.15	18363.86
	AL 2024	700.50	10.62	7439.33
	Ni-Superalloy	2129.86	5.89	12544.88
	High-Strength Steel	799.68	4.82	3857.65
	Ti64	1064.93	5.53	5889.06
Systems	AL 2024	2103.2	10.62	22335.98
	High-Strength Steel	1577.4	4.824	7609.378
	Copper	1051.6	1.51	1587.97
Furnishing	CFRP	3981.21	11.155	44410.4
Operator Items	AL 2024	3316.66	10.62	35222.93
	CFRP	3316.66	11.15	36997.34
			RD0004	**451802.6**

Table A. 7: Total energy necessary for manufacturing for the MHEP

D250-TFLH2-MHEP				
Module	**Material**	**Mass [kg]**	**Amount[kWh]**	**RD0004**
Structure	CFRP	10069.19	11.15	112321.8
	AL 2024	13865.33	10.62	147249.8
	High-Strength Steel	3122.29	4.824	15061.93
	Ti64	935.22	5.53	5171.77
Power Unit	CFRP	1744.42	11.15	19459.01
	AL 2024	727.665	10.62	7727.80

	Ni-Superalloy	2229.19	5.89	13129.93
	High-Strength Steel	445.84	4.824	2150.72
	Ti64	1114.59	5.53	6163.71
Systems	AL 2024	5311.47	10.62	56407.83
	Steel	1729.43	4.824	8342.77
	Copper	1148.33	1.51	1733.97
	CFRP	201.48	11.15	2247.531
Furnishing	CFRP	2353.34	11.15	26251.55
Operator Items	AL 2024	3316.66	10.62	26251.55
	CFRP	3316.66	11.1	35222.93
			RD0004	**484894.6**

Table A. 8: Overview of submodules and modularity across the three aircraft configurations.

		RE0004		
Modules	Submodules	D250-TF- FF	D250-TF-SF	D250-TFLH2-MHEP
Structure	Wing	1	1	0
	HTP	1	1	0
	VTP	1	1	0
	Fuselage	1	1	0
	Landing Gear	1	1	0
	Pylon	1	1	0
Power Unit	Nacelle	1	1	0
	Engine Systems	1	1	0
	Gearbox	1	1	0
	Gas Turbine	1	1	0

	Fan	1	1	0
Systems	Auxillary Power Unit	1	1	0
	Hydraulic Systems	1	1	0
	Air Conditioning	1	1	0
	DeIcing	1	1	0
	Fire Protection	1	1	0
	Flight Controls	1	1	0
	Instrument Panel	1	1	0
	Automatic Flight System	1	1	0
	Communication	1	1	0
	Electrical Systems	1	1	0
	Navigation	1	1	0
	LH2 Tank System	0	0	0
	LH2 Tank Structure	0	0	0
	Installation	0	0	0
	Thermal Management	0	0	0
	Cables	0	0	0
	Ass Idle	0	0	0
	E-Taxi System	0	0	0
	Power Electronics	0	0	0
	Fuel Cell Stack	0	0	0
	Fuel Cell Subsystems	0	0	0
Furnishing	Furnishing	1	1	1
Operator Items	Operator Items	1	1	1

Results	**70.59**	**70.59**	**5.88**

Table A. 9: EoL for D250-TF

D250-TF	Materials	Mass (kg)	Landfill [%]	Incineration [%]	Recycling [%]	Re-Use [%]	Incineration Energy [MJ]	Actual Recycling [%]
Structure	CFRP	9253.61	9.80	9.80	0.00	0.00	148057.76	0.00
	AL 2024	12636.13	5.35	0.00	21.42	0.00	0.00	20.35
	High-Strength Steel	2710.19	1.15	0.00	4.59	0.00	0.00	2.76
	Ti64	913.24	0.48	0.00	1.45	1.45	0.00	1.16
Power Unit	CFRP	1646.245	1.74	1.74	0.00	0.00	26339.92	0.00
	AL 2024	700.502	0.30	0.00	1.19	0.00	0.00	1.13
	Ni-Superalloy	2129.86	1.13	0.00	3.38	3.38	0.00	2.81
	High-Strength Steel	799.679	0.34	0.00	1.36	0.00	0.00	0.81
	Ti64	1064.93	0.56	0.00	1.69	1.69	0.00	1.35
Systems	AL 2024	2103.2	0.89	0.00	3.56	0.00	0.00	3.39
	High-Strength Steel	1577.4	0.67	0.00	2.67	0.00	0.00	1.60
	Copper	1051.6	0.56	0.00	1.67	1.67	0.00	1.40
Furnishing	CFRP	3981.21	4.22	4.22	0.00	0.00	63699.36	0.00
Operator Items	AL 2024	3316.66	1.41	0.00	5.62	0.00	0.00	5.34
	CFRP	3316.66	3.51	3.51	0.00	0.00	53066.56	0.00
Results			32.11	19.28	48.61	8.20	291163.60	32.11

Table A. 10: EoL for D250-TFLH2-MHEP

D250-TFLH2-MHEP	Materials	Mass (kg)	Landfill [%]	Incineration [%]	Recycling [%]	Re-Use [%]	Incineration Energy [MJ]	Actual Recycling [%]
Structure	CFRP	10069.19	9.75	9.75	0.00	0.00	161107.04	0.00

	AL 2024	13865.33	5.37	0.00	21.48	0.00	0.00	20.41
	High-Strength Steel	3122.29	1.21	0.00	4.84	0.00	0.00	2.90
	Ti64	935.22	0.45	0.00	1.36	1.36	0.00	1.09
Power Unit	CFRP	1744.42	1.69	1.69	0.00	0.00	27910.72	0.00
	AL 2024	727.665	0.28	0.00	1.13	0.00	0.00	1.07
	Ni-Superalloy	2229.19	1.08	0.00	3.24	3.24	0.00	2.69
	High-Strength Steel	445.838	0.17	0.00	0.69	0.00	0.00	0.41
	Ti64	1114.595	0.54	0.00	1.62	1.62	0.00	1.30
Systems	AL 2024	5311.47	2.06	0.00	8.23	0.00	0.00	7.82
	Steel	1729.43	0.67	0.00	2.68	0.00	0.00	1.61
	Copper	1148.33	0.56	0.00	1.67	1.67	0.00	1.40
	CFRP	201.48	0.20	0.20	0.00	0.00	3223.71	0.00
Furnishing	CFRP	2353.34	2.28	2.28	0.00	0.00	37653.50	0.00
Operator Items	AL 2024	3316.66	1.28	0.00	5.14	0.00	0.00	4.88
	CFRP	3316.66	3.21	3.21	0.00	0.00	53066.56	0.00
D250-TFLH2-MHEP	**Materials**	**Mass (kg)**	**30.80**	**17.13**	**52.07**	**7.88**	**282961.53**	**45.58**

A.2 MATLAB SCRIPT FOR PREDICTED VALUES

In this section, the script used to compute the predicted values for the RD.0013 used as an example in Chapter 5, is presented.

```
metric_name = 'RD.0013';

x_data = [81.66, 81.66, 62.77];
y_data = [4, 4, 3];
% Anchor points
x_anchor = [0, 100];
y_anchor = [1, 5];
x_all = [x_data, x_anchor];
y_all = [y_data, y_anchor];

% Group by unique x-values and average y-values manually
[x_unique, ~, ic] = unique(x_all);
y_grouped = zeros(size(x_unique));
for i = 1:length(x_unique)
    y_grouped(i) = mean(y_all(ic == i));
end

% Fit a linear regression trend line using all points
p_linear = polyfit(x_all, y_all, 1);
x_fit = linspace(0, 100, 200);
y_fit_linear = polyval(p_linear, x_fit);

% Compute predicted values from the linear trend for original x_data
y_linear_pred = polyval(p_linear, x_data);
```

```
% Plotting
figure;
hold on;
grid on;

% Plot original data points (blue)
scatter(x_data, y_data, 100, 'b', 'filled', 'DisplayName', 'Original Data');

% Plot anchor points (black)
scatter(x_anchor, y_anchor, 50, 'k', 'filled', 'DisplayName', 'Anchors');

% Plot linear trend (dashed red)
plot(x_fit, y_fit_linear, 'r--', 'LineWidth', 2, 'DisplayName', 'Linear Trend');

% Plot piecewise line through averaged points (solid black)
plot(x_unique, y_grouped, 'k-', 'LineWidth', 2, 'DisplayName', 'Interpolation curve');

% Plot predicted points from linear trend (magenta)
scatter(x_data, y_linear_pred, 100, 'm', 'filled', 'DisplayName', 'Predicted Points (Linear)');

% Annotate predicted values
for i = 1:length(x_data)
    txt = sprintf('%.2f', y_linear_pred(i));
    text(x_data(i) + 2, y_linear_pred(i), txt, 'FontSize', 9, 'Color', 'm');
end
```

```
xlabel('Percentage of recyclable materials');
ylabel('Rating');
title(['Trend for RD.0013 ']);
xlim([0 100]);
ylim([1 5]);
legend('Location', 'best');
box on;
y_piecewise = interp1(x_unique, y_grouped, x_data, 'linear');
disp(['Predicted Y values from LINEAR trend (', metric_name, '):']);
disp(y_linear_pred);
disp(['Predicted Y values from interpolation curve line (', metric_name, '):']);
disp(y_piecewise);
print(gcf, 'Percentage of recyclable materials_MAUT', '-dpng', '-r300');
```