ANTONIA RAHN

IT'S TIME FOR SUSTAINABLE AVIATION

DISCRETE-EVENT LIFE CYCLE ASSESSMENT OF EMERGING AIRCRAFT TECHNOLOGIES

It's Time for Sustainable Aviation

Discrete-Event Life Cycle Assessment
of Emerging Aircraft Technologies

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Preface

Like many scientists, I have always been curious and eager to understand new things, discover the world, and look beyond the familiar. Travelling has therefore always been an important part of my life and was also one of the reasons why I chose to study aerospace engineering in the first place. During my studies, however, I increasingly found myself asking an uncomfortable question: How much longer can we continue to fly in the face of environmental challenges?

I joined the Fridays for Future movement because I felt that far too little was happening. At the same time, I was studying a subject that fascinated me deeply, despite the significant environmental impact of aviation. Yet in my studies, I learned very little about how aviation could become more sustainable, or about what it would take to achieve it. This realisation ultimately shaped the focus of my doctoral research.

I was fortunate to have the opportunity to design my own research topic at DLR. I quickly realised that environmental problems extend far beyond CO_2 emissions and that life cycle assessment is an incredibly powerful method. Combining it with discrete-event simulation allowed me to take it a step further by explicitly integrating temporal aspects into environmental assessments. New aircraft technologies do not emerge in a static system; they evolve over time and unfold their impacts across long life cycles. This insight shaped the direction of my research. I wanted to understand innovative aircraft technologies in their full context: across their entire life cycle and throughout their development over time. This perspective also inspired the title of this dissertation:

"It's Time for Sustainable Aviation"

For me, this title has two meanings. On the one hand, my work quite literally deals with time and how it can be incorporated into the environmental life cycle assessment of new aircraft technologies. On the other hand, the title also represents urgency. Now is the time to move sustainable aviation from vision to reality.

Over the past few years, conversations with researchers, aircraft designers, maintenance engineers, and political decision-makers have given me many different perspectives on the future of aviation. Many of the innovative technologies we are talking about today have been under discussion for decades. And yet, progress often remains slow. One of the key insights I have taken from this dissertation is that time is not only something we need to represent more carefully in our methods; it is a real constraint. We do not have an unlimited amount of it. This dissertation cannot solve the challenges facing aviation. I hope, however, that it contributes to a better understanding of emerging technologies and supports more informed decision-making towards sustainable aviation.

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Summary

Global air traffic is growing rapidly and is projected to expand over the next decades. This growth is in direct tension with international climate targets. Aviation is a significant contributor to global emissions, and emerging aircraft technologies, such as hydrogen-powered and hybrid-electric concepts, offer potential for emission reductions. Yet, their environmental performance remains difficult to assess. Life cycle assessment is an established method for evaluating a wide range of environmental impact indicators throughout the life cycle of an aircraft. Conventional life cycle assessment approaches rely on static, averaged assumptions of aircraft operation and often neglect the dynamic interplay of flight events, maintenance constraints, and component replacement cycles.

This dissertation comprises five interconnected studies that develop a discrete-event life cycle assessment framework and apply it to both conventional and novel aircraft concepts. The framework models the entire aircraft lifetime as time-explicit events, with particular emphasis on maintenance activities and flight operations, thereby capturing the dynamic nature of the aircraft life cycle.

Maintenance activities remain vastly underrepresented and are often dismissed as environmentally negligible despite being a mandatory precondition for safe and continued flight operations. To address this, a top-down analysis of maintenance checks is combined with a bottom-up assessment of individual tasks derived from the aircraft manufacturer's maintenance planning document. The results show that the environmental impacts are not evenly distributed throughout the life of the aircraft. Especially heavy maintenance checks, engine shop visits, and certain component replacements lead to substantially higher impacts while associated aircraft downtimes directly reduce transport capacity. Maintenance-related impacts are further shown to be highly sensitive to factors such as the flight schedule or maintenance management practices.

Flight operations present an equally fundamental challenge. Around one third of aviation's climate impact stems from carbon dioxide (CO_2) emissions, while the remaining share arises from non-CO_2 effects, such as contrail formation, water vapour, or nitrogen oxides (NO_X). These are highly dependent on flight altitude, routing, and atmospheric conditions and cannot be adequately captured by conventional life cycle assessment approaches. Coupling the discrete-event life cycle assessment with an atmospheric climate response model enables the assessment of aircraft across different operational conditions. This is demonstrated through a comparative analysis of a turbofan and a turboprop aircraft with different flight schedules and fuel types. The results highlight that integrating non-CO_2 effects into life cycle assessment substantially improves the representativeness of environmental assessments in aviation.

These methodological foundations are subsequently applied to two emerging aircraft concepts with distinct technological characteristics. The first is a hydrogen-powered aircraft with cryogenic liquid hydrogen tanks, an integrated fuel cell system, and an advanced hydrogen propulsion and distribution system. Existing life cycle assessment studies of hydrogen-powered aircraft rarely account for the operational implications of novel maintenance requirements and largely overlook uncertainties arising from the limited data availability of prospective technologies. To address these gaps, the discrete-event life cycle assessment is combined with probabilistic uncertainty characterisation. While hydrogen technologies can substantially reduce overall environmental impacts relative to conventional aircraft, these benefits come with important trade-offs: production and maintenance of additional components generate higher on-ground impacts, and new safety requirements introduce longer and more frequent maintenance downtimes that reduce operational capacity. The hydrogen tank emerges as a particularly critical component, given its uncertain in-service lifetime and material-intensive replacement.

The second concept is a hybrid-electric aircraft, with batteries being a key determinant of its environmental impact. A semi-empirical battery degradation model is integrated into the discrete-event life cycle assessment framework to represent charging strategies, battery ageing, and replacement cycles. The results reveal a trade-off between operational efficiency and environmental performance. Longer turnaround times enable slower charging, which is less damaging to the battery and reduces the number of replacements over the aircraft lifetime, while lowering both life cycle CO_2 emissions and material demand. This benefit, however, comes at the cost of lower aircraft utilisation.

Across all studies, the findings confirm that the operational phase remains the dominant contributor to aviation's environmental impact. At the same time, ground-based life cycle phases reveal burden-shifting effects that static assessment approaches systematically overlook. The developed discrete-event life cycle assessment framework therefore advances dynamic assessment methodology for aviation and provides a more realistic basis for evaluating emerging aircraft technologies.

Samenvatting

Samenvatting Het wereldwijde luchtverkeer groeit snel en zal naar verwachting de komende decennia verder toenemen. Deze groei staat haaks op de internationale klimaatdoelstellingen. De luchtvaart draagt aanzienlijk bij aan wereldwijde emissies, en nieuwe vliegtuigtechnologieën, zoals waterstofaangedreven en hybride-elektrische concepten, hebben de potentie om emissies te reduceren. Hun milieuprestaties blijven echter moeilijk te beoordelen. De levenscyclusanalyse is een gevestigde methode voor het beoordelen van een breed scala aan milieu-indicatoren over de volledige levenscyclus van een vliegtuig. Conventionele benaderingen van levenscyclusanalyses zijn gebaseerd op statische, gemiddelde aannames over de vluchtuitvoering, en verwaarlozen vaak de dynamische wisselwerking tussen vluchtgebeurtenissen, onderhoudsbeperkingen en vervangingscycli van componenten.

Dit proefschrift omvat vijf onderling samenhangende studies die een framework voor discrete-event levenscyclusanalyse ontwikkelen en toepassen op zowel conventionele als nieuwe vliegtuigconcepten. Het framework modelleert de volledige levensduur van een vliegtuig als een tijdsexpliciete opeenvolging van gebeurtenissen, met specifieke nadruk op onderhoudsactiviteiten en vluchtoperaties, en neemt daardoor de dynamische aard van de levenscyclus van een vliegtuig mee.

Onderhoudsactiviteiten zijn doorgaans sterk ondervertegenwoordigd en worden vaak als ecologisch verwaarloosbaar beschouwd, ondanks dat zij een noodzakelijke voorwaarde vormen voor een veilige en continue vluchtuitvoering. Om dit aan te pakken wordt een top-downanalyse van onderhoudscontroles gecombineerd met een bottom-up-beoordeling van individuele onderhoudstaken, gebaseerd op het onderhoudsplanningsdocument van de vliegtuigfabrikant. De resultaten tonen aan dat de milieueffecten niet gelijkmatig over de levensduur van een vliegtuig zijn verdeeld. Met name omvangrijke onderhoudscontroles, revisies van vliegtuigmotoren en het vervangen van bepaalde componenten leiden tot aanzienlijk hogere milieueffecten, terwijl de bijbehorende stilstandstijden de transportcapaciteit direct verminderen. Daarnaast blijkt dat de milieueffecten van onderhoud sterk afhankelijk zijn van factoren zoals het vluchtschema en het onderhoudsmanagement.

De vluchtuitvoering vormt een even fundamentele uitdaging. Ongeveer een derde van de klimaatimpact van de luchtvaart is toe te schrijven aan koolstofdioxide-emissies (CO_2), terwijl het overige deel wordt veroorzaakt door niet-CO_2-effecten, zoals condensstrepen, waterdamp en stikstofoxiden (NO_X). Deze effecten zijn sterk afhankelijk van de vlieghoogten, vliegroutes en atmosferische omstandigheden en kunnen met conventionele levenscyclusanalysebenaderingen niet adequaat worden meegenomen. Het koppelen

van discrete-event-gebaseerde levenscyclusanalyse aan een atmosferisch klimaatmodel maakt het mogelijk om vliegtuigen onder verschillende operationele omstandigheden te beoordelen. Dit wordt aangetoond aan de hand van een vergelijkende analyse van een turbofan- en een turbopropvliegtuig met verschillende vluchtschema's en brandstoffen. De resultaten tonen aan dat de integratie van niet-CO2-effecten in de levenscyclusanalyse de representativiteit van milieubeoordelingen binnen de luchtvaart aanzienlijk verbetert.

Deze methodologische grondslagen worden vervolgens toegepast op twee nieuwe vliegtuigconcepten met verschillende technologische eigenschappen. Het eerste concept betreft een waterstofaangedreven vliegtuig met cryogene vloeibare-waterstoftanks, een geïntegreerd brandstofcelsysteem en een nieuw waterstofaandrijvings- en distributiesysteem. Bestaande levenscyclusanalyses van waterstofaangedreven vliegtuigen houden slechts beperkt rekening met de operationele gevolgen van nieuwe onderhoudsvereisten en verwaarlozen grotendeels de onzekerheden die voortvloeien uit de beperkte beschikbaarheid van gegevens voor toekomstige technologieën. Om deze lacunes te dichten, wordt de discrete-event-gebaseerde levenscyclusanalyse gecombineerd met een probabilistische onzekerheidskarakterisering. Hoewel waterstoftechnologieën de totale milieueffecten ten opzichte van conventionele vliegtuigen aanzienlijk kunnen verminderen, gaan deze voordelen gepaard met belangrijke compromissen. De productie en het onderhoud van aanvullende componenten veroorzaken hogere milieueffecten in de grondgebonden levenscyclusfasen, terwijl nieuwe veiligheidseisen leiden tot langere en frequentere onderhoudsstilstanden, waardoor de transportcapaciteit afneemt. De waterstoftank blijkt daarbij een bijzonder kritische component te zijn, aangezien zowel de onzekere gebruikslevensduur als de materiaalintensieve vervanging een wezenlijke bijdrage leveren aan de milieueffecten.

Het tweede concept betreft een hybride-elektrisch vliegtuig, waarbij de batterij een belangrijke determinant is voor de milieueffecten. Een semi-empirisch batterijdegradatiemodel is in het framework voor de discrete-event-gebaseerde levenscyclusanalyse geïntegreerd om laadstrategieën, batterijveroudering en vervangingscycli te modelleren. De resultaten tonen een afruil tussen operationele efficiëntie en milieuprestaties. Langere grondtijden maken langzamer laden mogelijk, waardoor de batterij minder wordt belast en het aantal batterijvervangingen gedurende de levensduur van het vliegtuig afneemt. Dit leidt zowel tot lagere levenscyclusgebonden CO_2-emissies als tot een lagere materiaalvraag. Dit voordeel gaat echter gepaard met een lagere benuttingsgraad van het vliegtuig.

In alle studies tonen de resultaten aan dat de operationele fase de grootste bijdrage blijft leveren aan de milieueffecten van de luchtvaart. Tegelijkertijd laten de grondgebonden levenscyclusfasen een verschuiving van milieueffecten zien die met statische beoordelingsmethoden niet kan worden vastgesteld. Het ontwikkelde framework voor discrete-event-gebaseerde levenscyclusanalyse levert daarmee een bijdrage aan de verdere ontwikkeling van dynamische beoordelingsmethoden binnen de luchtvaart en biedt een realistischere basis voor de analyse van nieuwe vliegtuigtechnologieën.

Zusammenfassung

Das weltweite Luftverkehrsaufkommen wächst kontinuierlich und wird voraussichtlich in den nächsten Jahrzehnten weiter zunehmen. Dieses Wachstum steht in direktem Widerspruch zu den internationalen Klimazielen. Der Luftverkehr trägt erheblich zu den globalen Emissionen bei und neue Flugzeugtechnologien wie wasserstoffbetriebene und hybrid-elektrische Konzepte bieten Potenzial für Emissionsminderungen. Jedoch ist ihre Umweltleistung nach wie vor schwer zu bewerten. Die Ökobilanzierung ist eine etablierte Methode zur Bewertung einer Vielzahl von Umweltindikatoren über den gesamten Lebenszyklus eines Flugzeugs hinweg. Herkömmliche Ansätze der Lebenszyklusanalyse stützen sich auf statische, gemittelte Annahmen über den Flugbetrieb und vernachlässigen häufig das dynamische Zusammenspiel von Flugereignissen, Wartungsbeschränkungen und Austauschzyklen von Komponenten.

Diese Dissertation umfasst fünf miteinander verknüpfte Studien, in denen ein diskret-ereignisbasiertes Ökobilanzierungsframework entwickelt und sowohl auf konventionelle als auch auf neuartige Flugzeugkonzepte angewendet wird. Das Framework bildet die gesamte Lebensdauer eines Flugzeugs als zeitlich explizite Abfolge von Ereignissen ab. Dabei liegt ein besonderer Fokus auf Wartungsmaßnahmen und Flugoperationen, wodurch die dynamische Natur des Flugzeuglebenszyklus berücksichtigt wird.

Wartungsmaßnahmen sind in der bisherigen Forschung stark unterrepräsentiert und werden häufig als ökologisch vernachlässigbar angesehen, obwohl sie eine zwingende Voraussetzung für einen sicheren und kontinuierlichen Flugbetrieb darstellen. Zur Schließung dieser Forschungslücke wird eine Top-down-Analyse von Wartungschecks mit einer Bottom-up-Bewertung einzelner Wartungsaufgaben kombiniert, die auf dem Wartungsplanungsdokument des Flugzeugherstellers basiert. Die Ergebnisse zeigen, dass die Umweltwirkungen nicht gleichmäßig über die Lebensdauer eines Flugzeugs verteilt sind. Insbesondere umfangreiche Wartungschecks, Triebwerksüberholungen sowie der Austausch bestimmter Komponenten führen zu deutlich höheren Umweltwirkungen, während die damit verbundenen Stillstandszeiten die Transportkapazität unmittelbar verringern. Darüber hinaus zeigt sich, dass wartungsbedingte Umweltwirkungen in hohem Maße von Faktoren wie dem Flugplan oder dem Wartungsmanagement abhängen.

Der Flugbetrieb stellt eine ebenso grundlegende Herausforderung dar. Rund ein Drittel der Klimawirkung der Luftfahrt ist auf Kohlendioxidemissionen (CO_2) zurückzuführen, während der verbleibende Anteil durch Nicht-CO_2-Effekte wie Kondensstreifenbildung, Wasserdampf oder Stickoxide (NO_X) verursacht wird. Diese Effekte hängen maßgeblich von Flughöhe, Flugroute und atmosphärischen Bedingungen ab und können mit konventionellen Ökobilanzierungsansätzen nicht angemessen erfasst werden. Durch die

Kopplung der diskret-ereignisbasierten Ökobilanzierung mit einem atmosphärischen Klimamodell wird die Bewertung von Flugzeugen unter unterschiedlichen Betriebsbedingungen ermöglicht. Dies wird anhand einer vergleichenden Analyse eines Turbofan- und eines Turbopropflugzeugs mit unterschiedlichen Flugplänen und Kraftstoffen demonstriert. Die Ergebnisse zeigen, dass die Integration von Nicht-CO_2-Effekten in die Ökobilanzierung die Repräsentativität von Umweltbewertungen in der Luftfahrt wesentlich verbessert.

Diese methodischen Grundlagen werden anschließend auf zwei neuartige Flugzeugkonzepte mit unterschiedlichen technologischen Eigenschaften angewendet. Das erste Konzept ist ein wasserstoffbetriebenes Flugzeug mit kryogenen Flüssigwasserstofftanks, einem integrierten Brennstoffzellensystem sowie einem neuartigen Wasserstoffantriebs- und -verteilungssystem. Bestehende Ökobilanzstudien zu wasserstoffbetriebenen Flugzeugen berücksichtigen die betrieblichen Auswirkungen neuartiger Wartungsanforderungen nur selten und vernachlässigen weitgehend die Unsicherheiten, die aus der begrenzten Datenverfügbarkeit zukünftiger Technologien resultieren. Zur Schließung dieser Lücken wird die diskret-ereignisbasierte Ökobilanzierung mit einer probabilistischen Unsicherheitscharakterisierung kombiniert. Obwohl Wasserstofftechnologien die gesamten Umweltwirkungen gegenüber konventionellen Flugzeugen erheblich reduzieren können, gehen diese Vorteile mit wesentlichen Kompromissen einher. Die Herstellung und Wartung zusätzlicher Komponenten verursachen höhere bodengebundene Umweltwirkungen, während neue Sicherheitsanforderungen längere und häufigere Wartungsstillstände erforderlich machen und dadurch die Transportkapazität verringern. Der Wasserstofftank erweist sich dabei als besonders kritische Komponente, da sowohl seine Einsatzlebensdauer mit erheblichen Unsicherheiten behaftet ist als auch sein materialintensiver Austausch einen wesentlichen Beitrag zu den Umweltwirkungen leistet.

Das zweite Konzept ist ein hybridelektrisches Flugzeug, bei dem die Batterie einen entscheidenden Einfluss auf die Umweltwirkungen besitzt. Zur Abbildung von Ladestrategien, Batteriealterung und Austauschzyklen wird ein semiempirisches Batteriedegradationsmodell in das diskret-ereignisbasierte Ökobilanzierungsframework integriert. Die Ergebnisse zeigen einen Zielkonflikt zwischen betrieblicher Effizienz und Umweltleistung. Längere Bodenzeiten ermöglichen langsamere Ladevorgänge, wodurch die Batterie weniger beansprucht wird und sich die Anzahl der Batteriewechsel über die Lebensdauer des Flugzeugs reduziert. Dies führt sowohl zu geringeren lebenszyklusbezogenen CO_2-Emissionen als auch zu einem geringeren Materialbedarf. Dieser Vorteil ist jedoch mit einer geringeren Auslastung des Flugzeugs verbunden.

Über alle Studien hinweg zeigen die Ergebnisse, dass die Betriebsphase weiterhin den größten Anteil an den Umweltwirkungen der Luftfahrt hat. Gleichzeitig zeigen die bodengebundenen Lebenszyklusphasen eine Verlagerung von Umweltwirkungen, die mit statischen Bewertungsverfahren nicht erfasst werden können. Das entwickelte diskret-ereignisbasierte Ökobilanzierungsframework stellt somit einen Beitrag zur Weiterentwicklung dynamischer Bewertungsmethoden in der Luftfahrt dar und schafft eine realistischere Grundlage für die Analyse neuartiger Flugzeugtechnologien.

Abbreviations

AFRP Aramid Fibre-Reinforced Plastic

AP Acidification Potential

APU Auxiliary Power Unit

ASK Available Seat Kilometre

ATA Air Transport Association

ATR Average Temperature Response

CA Criticality Analysis

CC Climate Change

CeRAS Central Reference Aircraft data System

CFRP Carbon Fibre-Reinforced Plastic

CIC Contrail-Induced Cloudiness

CMP Concentration of Mine Production

DLR German Aerospace Center

DoD Depth of Discharge

ECF Energy Carriers

EF Environmental Footprint

EIO-LCA Economic Input-Output Life Cycle Assessment

ESSENZ Integrated Method to Assess Resource Efficiency

EXACT Exploration of Electric Aircraft Concepts and Technologies

FAL Final Assembly Line

FC Flight Cycle

FEP Freshwater Eutrophication

FETP Freshwater Ecotoxicity

FH Flight Hour

FSNC Full-Service Network Carrier

GFRP Glass Fibre-Reinforced Plastic

GHG Greenhouse Gas

GPU Ground Power Unit

GRIDLAB Global Air Traffic Emission Distribution Laboratory

GSE Ground Support Equipment

GTP Global Temperature Potential

GWP Global Warming Potential

HTP Horizontal Tail Plane

HVAC Heating, Ventilation, and Air Conditioning

IATA International Air Transport Association

ICAO International Civil Aviation Organization

IPCC Intergovernmental Panel on Climate Change

IR Ionising Radiation

LCA Life Cycle Assessment

LCC Low Cost Carrier

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LH_2 Liquid Hydrogen

LLP Life Limited Part

LNB Large Narrow Body

LTO Landing to Take-Off

LYFE Life Cycle Cash Flow Environment

$LYFE^2$ Life Cycle Analysis Framework for Environment & Economics

MHEP Mild Hybrid-Electric Propulsion

MM Minerals and Metals

MPD Maintenance Planning Document

MRO Maintenance, Repair, and Overhaul

NMC Nickel-Manganese-Cobalt

ODP Ozone Depletion Potential

OEW Operating Empty Weight

P-LCA Process-Based Life Cycle Assessment

PAMELA Process of Advanced Management of End-of-Life of Aircraft

PAX Passenger

PEM Proton Exchange Membrane

PHEP Plug-In Hybrid-Electric Propulsion

POF Photochemical Ozone Formation

PtL Power-to-Liquid

RQ Research Question

S-LCA Streamlined Life Cycle Assessment

SAF Sustainable Aviation Fuel

SNB Short Narrow Body

SoC State of Charge

TCM Trajectory Calculation Module

TEP Terrestrial Ecotoxicity

VTP Vertical Tail Plane

Chapter 1

General Introduction

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1.1. Towards Sustainable Aviation

The aviation industry is currently undergoing a fundamental technological transformation [1]. As a near-term measure, Sustainable Aviation Fuels (SAFs) are increasingly being integrated into existing fleets as drop-in solutions [2]. At the same time, novel concepts, such as electric, hybrid-electric, or hydrogen-powered aircraft, are promoted as the next generation of key technologies to reduce the environmental footprint of aviation [1, 3]. Yet, a critical question remains difficult to answer: are they really more sustainable, or does their apparent benefit come with hidden environmental trade-offs?

There is no simple answer to this question. But with the rapid growth in air traffic [4] and increasing pressure to decarbonise [5], it can no longer be ignored. By far the largest share of an aircraft's environmental impact is commonly associated with flight operations [6]. Fuel burn, in-flight emissions, and operational efficiency are, therefore, the metrics by which sustainability is most often judged. However, this consideration tells only part of the story: an aircraft's footprint accumulates across its entire life cycle, from the production and supply of aircraft materials to manufacturing, maintenance, and end-of-life treatment. A technology that performs well during flight may simply relocate its impact elsewhere, for instance, into a more resource-intensive supply chain, a shorter component lifetime, or more complex maintenance activities. Aircraft designers, operators, and policymakers depend on a reliable answer to guide investment and regulation towards technologies that deliver genuine benefit.

SAFs illustrate this conflict well: As a near-term mitigation option, they are considered particularly promising due to their compatibility with existing aircraft engines and fuelling infrastructure [2, 7]. Their use can achieve substantial Greenhouse Gas (GHG) emission reductions compared to conventional jet fuel, although the magnitude of these reductions varies strongly across different production pathways [8]. However, their large-scale deployment remains constrained by feedstock availability, production capacity, and competing demands from other sectors [9, 10]. At the same time, scaling up SAF extends beyond fuel production and requires coordinated adaptations across the broader aviation and energy systems, particularly in supply chains and airport infrastructure [8].

Novel propulsion concepts, on the other hand, raise a structurally different challenge. Both direct combustion and fuel cell technologies are being explored as potential long-term solutions. Hydrogen-based propulsion concepts have a high potential to reduce in-flight emissions, as burning hydrogen does not emit carbon dioxide (CO_2) and primarily produces water vapour [11]. Challenges associated with cryogenic storage, ground handling, and safety requirements represent barriers to implementation, although ongoing research activities aim to address these issues [11, 12]. The production of dedicated components, such as cryogenic tanks and fuel cell systems, introduces additional manufacturing-related impacts [13]. In contrast, hybrid-electric configurations combine conventional propulsion with electric components to improve efficiency and reduce emissions [14]. Especially the use of batteries presents challenges in terms of charging infrastructure, battery management, and battery durability [15]. These effects can have a direct impact on operational and maintenance schedules, which can add up significantly over the course of an aircraft's long service life. The deployment of these technologies also increases the demand for critical raw materials, including lithium, cobalt, nickel, and

titanium. As demand for these materials continues to grow, pressure on global supply chains and the availability of resources is expected to increase, which poses additional challenges for the long-term sustainability and resilience of the aviation sector [16, 17].

These examples demonstrate that environmental impacts can no longer be evaluated solely on the basis of operational emissions. Instead, a life cycle perspective is required to capture environmental impacts across all stages of an aircraft's life cycle [18, 19]. Assessing these impacts reliably requires a dedicated methodology.

1.2. Methodological Foundations of Life Cycle Assessment in Aviation

Given the complexity of emerging aircraft technologies and their diverse environmental impacts across all life cycle stages, Life Cycle Assessment (LCA) has become a widely used methodology for evaluating environmental performance in aviation [20]. LCA is standardised under ISO 14040/44 [21, 22] and provides a systematic framework for assessing the environmental impacts of products and systems across their entire life cycle. Its applications include identifying improvement potentials in different life cycle stages, comparing products with the same function, and supporting decision-making in product development. The LCA framework comprises four phases, which are interdependent and interact closely with each other. Their relationship is illustrated in Figure 1.1. They consist of a goal and scope definition, a Life Cycle Inventory (LCI), a Life Cycle Impact Assessment (LCIA), and an interpretation.

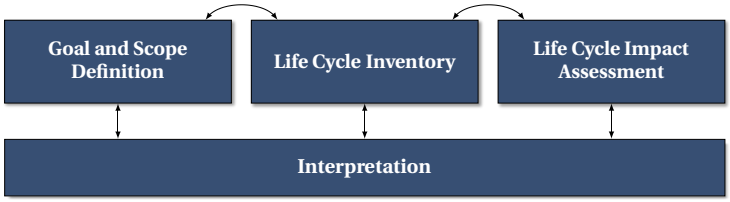


Figure 1.1: LCA framework based on ISO 14040/44 [21, 22].

In the goal and scope phase, the intended application, system boundaries, functional unit, and methodological choices are defined, which strongly influence the overall assessment results. Aircraft systems can be evaluated at different levels, such as per Available Seat Kilometre (ASK), per flight, or over the entire aircraft lifetime [23]. The choice of the functional unit significantly influences the interpretation of results, particularly when comparing emerging technologies with different performance characteristics, payload capacities, or operational ranges. Similarly, system boundaries may extend beyond flight operations to include energy production, airport infrastructure, and material supply chains [23], all of which become increasingly relevant for novel propulsion technologies.

The LCI phase involves the collection and quantification of material and energy flows as well as emissions associated with the product system. The LCI phase in aviation is characterised by a high degree of data complexity and uncertainty [24]. Aircraft systems operate over long service lifetimes and involve numerous discrete operational and main-

tenance events. However, detailed data on flight emissions and on-ground processes is limited, particularly for emerging technologies. Replacement cycles for major components, technological upgrades, and evolving operational patterns can significantly influence environmental impacts over time. As a result, LCAs in aviation often rely on assumptions or aggregated data [25], which may obscure important system-level dynamics and should therefore be transparently documented.

During the LCIA, elementary flows are translated into environmental impacts using characterisation models. Depending on the methodological approach, assessments may focus on specific environmental problems (midpoint methods) or on aggregated damage indicators (endpoint methods), such as impacts on human health or ecosystems. Climate impacts during flight operations introduce additional methodological considerations. Especially the altitude- and location-dependent non-CO_2 effects can currently not be adequately captured by existing LCIA methods.

Finally, the interpretation phase evaluates the results in relation to the original study objectives, considering uncertainties, assumptions, and methodological limitations. Sensitivity and uncertainty analyses are often applied to support robust conclusions and decision-making [26]. Furthermore, conventional LCA approaches are typically based on static representations of product systems, assuming fixed operational conditions and averaged lifetime performance. In contrast, aircraft systems exhibit dynamic behaviour. Technological learning effects and potential changes in energy supply over time further complicate their interactions [27]. For emerging aviation technologies, such dynamic aspects may significantly affect the distribution and magnitude of environmental impacts across life cycle stages. Capturing these temporal and operational dynamics remains a key methodological challenge for robust assessments in aviation.

Several studies have applied LCA to aviation systems, primarily focusing on conventional aircraft technologies or alternative fuel pathways [28–30]. These studies generally highlight the dominant contribution of the operational phase to overall environmental impacts. However, emerging propulsion concepts and alternative energy carriers increasingly shift environmental burdens towards other ground-based life cycle stages, including manufacturing, infrastructure, and maintenance processes [31, 32]. At the same time, limited data availability introduces significant uncertainties that are often insufficiently captured by conventional LCA approaches [25]. Methodological developments are required to enable more comprehensive and dynamic environmental assessments of future aviation technologies.

1.3. Knowledge Gaps and Research Questions

Despite increasing interest in applying LCA to emerging aircraft technologies, important methodological challenges remain insufficiently addressed. In particular, complex operational dynamics, long aircraft service lifetimes, and comprehensive coverage of all life cycle phases are often only partially represented in existing studies. The main objective of this dissertation is therefore

to develop and apply a methodological framework for life cycle assessment of emerging aircraft technologies.

Specifically, this dissertation develops a discrete-event LCA approach to capture operational dynamics and enable a more holistic environmental evaluation of aviation systems. Initially, the LCA framework is applied to conventional aircraft, with particular focus on flight operations and maintenance activities, as these are typically the most influential and complex life cycle phases.

The developed approach is subsequently applied to two innovative aircraft concepts: a hydrogen-powered Mild Hybrid-Electric Propulsion (MHEP) and a Plug-In Hybrid-Electric Propulsion (PHEP) aircraft. The aim of the analyses is to provide environmentally-driven insights for researchers, aircraft designers, operational stakeholders, and policy-makers to support informed decision-making regarding future technologies.

To contribute to this objective, five Research Questions (RQs) are defined:

Methodology-related Research Questions

RQ 1: How can discrete-event simulation be applied within life cycle assessment to provide a more comprehensive evaluation of environmental impacts across all life cycle phases of an aircraft?

RQ 2: What are the environmental implications of aircraft maintenance activities, and how can life cycle assessment methods capture these previously overlooked impacts?

RQ 3: How can incorporating non-CO_2 effects and operational scenarios improve the accuracy within life cycle assessments of aircraft?

Application-related Research Questions

RQ 4: What are the environmental impacts and associated uncertainties of new maintenance activities in hydrogen-powered aircraft, and how do they shape the overall life cycle footprint?

RQ 5: What are the environmental impacts and critical raw material demand of plug-in hybrid-electric aircraft, and how does turnaround time shape this trade-off?

The results contribute to advancing LCA methodologies for aviation. In addition, they provide insights into environmental trade-offs associated with emerging aircraft technologies and support more robust decision-making in the aviation sector.

1.4. Dissertation Outline

This dissertation comprises five studies, each presented as a stand-alone article in Chapters 2-6[1], followed by a general conclusion. Figure 1.2 illustrates the overall structure of the dissertation.

[1] Minor adjustments to references and the labelling of sections, figures, and tables have been made to ensure consistency throughout the dissertation. Brief clarifying additions have been made to the original text to aid interpretation; these do not alter the studies' methods, results, or conclusions.

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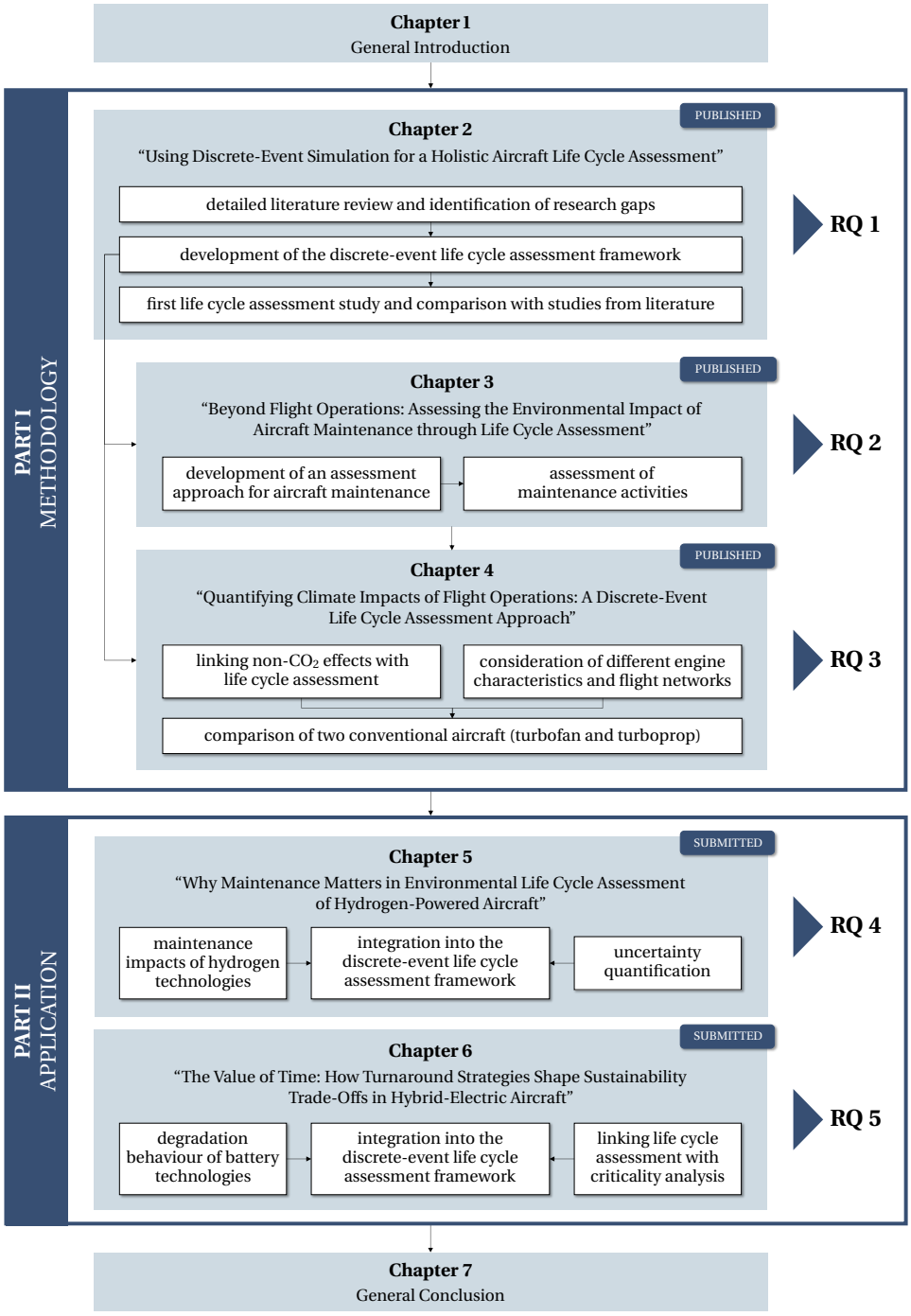


Figure 1.2: Schematic representation of the dissertation outline with an overview of the central topics of the stand-alone articles in Chapters 2-6.

As this dissertation follows a paper-based format, the chapter titles correspond to those of the underlying published or submitted articles. The chapters are ordered to build on each other logically, from methodology to application.

Part I focuses on the methodological development of the discrete-event LCA approach. First, a comprehensive literature review identifies existing research gaps in LCA of aircraft. Additionally, the discrete-event LCA framework is developed and applied to a conventional short- and medium-haul aircraft (Chapter 2). Subsequently, the most complex events in the aircraft life cycle are examined by assessing the environmental impacts of maintenance activities (Chapter 3) and the climate impacts of flight operations for different engine types (Chapter 4).

Part II then deals with the application of the developed LCA approach by adapting it to new aircraft technologies. Chapter 5 examines a hydrogen-powered aircraft, with particular emphasis on hydrogen storage, fuel cell and propulsion system, and their associated maintenance-related uncertainties. Chapter 6[2] then investigates the environmental trade-offs of a battery-powered PHEP aircraft, incorporating a battery degradation model to analyse the influence of turnaround strategy (on-board charging versus battery swapping). A Criticality Analysis (CA) further examines the associated demand for critical raw materials in relation to the number of batteries and turnaround time.

Finally, Chapter 7 concludes the findings of the individual studies and provides recommendations to researchers, LCA practitioners, and aviation stakeholders.

All studies are accompanied by supplementary material provided as spreadsheet files. These files contain the underlying inventories, simulation input and output data, and additional data supporting the analyses presented in the respective chapters. An overview of the supplementary material is provided in the Appendix, together with the corresponding access information. In several studies, the discussion focuses primarily on impacts related to Global Warming Potential (GWP), as this represents one of the most prominent indicators in the assessment of aviation technologies. However, the underlying LCAs comprise the full set of impact categories defined by the selected LCIA method. To ensure transparency and enable further interpretation, the supplementary material accompanying each study provides the complete set of LCIA results across all assessed impact categories.

[2] To preserve the original structure of the submitted journal manuscript, this chapter follows the journal's format, in which the Results section precedes the Methods section.

Part I –

Methodology

Chapter 2

Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment

With growing environmental awareness and the resulting pressure on aviation, ecological impact assessments are becoming increasingly important. Life cycle assessment has been widely used in the literature as a tool to assess the environmental impact of aircraft. However, due to the complexity of the method itself and the long lifespans of aircraft, most studies so far have made strong simplifications, especially concerning the operational phase. Using a combined discrete-event simulation framework, this paper aims to ecologically assess the individual life cycle phases of an aircraft. The method will be demonstrated on a case study of an A320 and subsequently compared with findings from the literature. Despite the significant environmental impact of flight operations, which covers almost 99.8 % of the entire life cycle of the aircraft, a detailed consideration of all life cycle phases is essential to serve as a reference for the ecological assessment of novel aircraft concepts. The presented assessment method thus enables a holistic analysis at an early stage of the design process and supports the decision-making for new technologies and operational changes.

This chapter is based on:
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2.1. Introduction

Aviation currently accounts for about 3.6 % of the total anthropogenic GHG emissions and is responsible for 13.4 % of emissions in the transport sector [33]. However, with the steady growth of air traffic due to globalisation, this environmental impact is increasing, and consequently, so is the need for alternative and sustainable aircraft concepts. There are different approaches to determining the environmental impact of such new aircraft technologies and their corresponding effect compared to conventional aircraft. One of the most well-established methods is LCA, which is defined according to DIN 14040/14044 and is used to assess the environmental impact of a product or a product system over all life cycle phases [21, 22]. An LCA can be divided into the following four steps:

- Goal and Scope
- LCI Analysis
- LCIA
- Interpretation

The first phase is used to define the goal and scope of the LCA. This includes, for example, the identification of system boundaries or a suitable functional unit. The purpose of the functional unit is to provide a detailed product description. This is intended to give a reference to which inventory data can be applied to ensure that different systems are comparable on a common basis. In addition, important assumptions and limitations are selected and documented on which the study is based. This is followed by the LCI analysis, the data collection part of the LCA. In this phase, all processes that belong to a product system are identified and the necessary resources, materials, and emissions are collected. The impact assessment then translates the collected inventory of the product system into environmental impacts. For this purpose, numerous methods that categorise and characterise the individual impacts of different processes and life cycle phases are available. The results are then multiplied by so-called impact factors and classified into suitable impact categories that combine different emissions into one or more environmental impacts [34]. In the final phase, the results of the LCA are interpreted and conclusions as well as recommendations are drawn. The study is therefore analysed on the basis of the defined goal and scope of the first phase. This includes an evaluation regarding its completeness based on the assumptions and limitations.

There are a number of publications that perform an LCA for aircraft components or whole aircraft. These studies show that the operational phase, comprising both flight operations and maintenance of the aircraft, contributes to the highest environmental impact. Johanning & Scholz [35], for example, claim that the use phase completely dominates the environmental impact of an aircraft with a share of 99.8 %, and many other authors come to similar conclusions [36–38]. In these studies, however, the operational phase is often analysed in a simplified way, e.g., by considering Flight Hours (FHs) as an average value per year or per total lifetime and by often neglecting maintenance events. Yet, especially the latter are essential for reliable flight operations and are themselves dependent on the flight schedule as their intervals are specified by, for instance, the number and duration of performed flights [39]. Additionally, overhaul or modification events

can increase the lifetime of an aircraft's components or improve its in-flight efficiency, which in turn positively affects the environmental impact. To dynamically link individual flight and maintenance events and thus depict a realistic operational schedule, a discrete-event simulation is a valuable option. In a discrete-event simulation, isolated aircraft events (such as flights or maintenance activities) are generated with certain attributes and executed at specific times during the simulation. This enables a detailed and accurate simulation of an aircraft's life cycle and rapid implementation of operational changes. In the context of this study, an existing discrete-event simulation, developed at the German Aerospace Center (DLR) Institute of Maintenance, Repair and Overhaul, which covers the entire life cycle of an aircraft from an economic point of view, will be extended with an environmental assessment. Thereby, an individual LCA is performed for each event, based on its operational parameters. This combined event simulation provides a detailed overall environmental impact for all aircraft life cycle phases, event categories, or time periods. Due to its generic structure, the simulation environment can be applied to different aircraft types, including both conventional and innovative ones. Especially with regard to the implementation of new technologies, possible environmental impacts can thus already be analysed in the development phase. In addition, the detailed analysis can indicate which design aspects still have potential for improvement and thereby support re-design and further decision-making.

The methodology is applied to a conventional aircraft comparable to an Airbus A320, which provides a solid data basis and can serve as a reference for the development of new aircraft concepts. The outcomes are then analysed and compared with existing findings from the literature. The study was carried out as part of and by using preliminary research from DLR's internal Exploration of Electric Aircraft Concepts and Technologies (EXACT) project, which aims, among other things, to assess the ecological effects of new aircraft technologies and their transportation systems. The structure of the chapter is divided into the following sections: First, a detailed literature review identifies how existing LCAs for aircraft are conducted. Here, particular attention is dedicated to their considered life cycle phases. Furthermore, publications combining LCA and discrete-event simulation are examined in more detail. In Section 2.3, the discrete-event simulation is described and further framework conditions for modelling the life cycle are given. Section 2.4 then describes the environmental assessment for each life cycle phase in detail. The results are presented in Section 2.5 and compared with the findings from the literature.

2.2. Literature Review

The starting point of this study is a detailed literature review, providing an overview of existing LCA studies in the context of aviation. Thereby, a selection of suitable publications is identified to provide comparative data. Additionally, possible options for environmentally enhanced discrete-event simulation are highlighted and reviewed. As there is a lack of studies investigating discrete-event simulation and LCA in the field of aviation, the latter are related to various other industrial sectors.

2.2.1. Life Cycle Assessment in Aviation

The ecological assessment of aircraft and their operation using LCA is not entirely new. Several studies have dealt with the topic and carried out environmental impact assessments in a wide range of applications. In 2013, Atılgan et al. [40] conducted an environmental impact assessment for a turboprop engine using an exergo-analysis. The related environmental impact of each component of the engine was first calculated and then an individual environmental performance was assigned to each component using the exergo rate. The combustion chamber was identified as having the highest environmental impact in the engine. Vinodh et al. [41] published an LCA for a turbine blade. By focusing on the manufacturing phase, environmental issues could be identified as early as in the machining process, thus enabling the development of more environmentally friendly aircraft components. The environmental impact of the maintenance of an engine was assessed by Şöhret et al. [42]. The author considered routine maintenance (based on electricity consumption and utilised fuel) of a Cessna 172 Skyhawk and concluded, among other things, that fuel is a significant contributor to impact categories such as the GWP, Acidification Potential (AP), or Photochemical Ozone Formation (POF), whereas electricity consumption dominates in the impact category of Ozone Depletion Potential (ODP). Altuntaş et al. [43] considered the use of an Auxiliary Power Unit (APU) and Ground Power Unit (GPU) for a ground power supply and compared them based on LCA results. The study showed that the use of GPU at the airport has significantly lower impacts on human health, ecosystem quality, and resources compared to an APU. Another way to minimise the environmental impact of aircraft is to use lighter materials. A comparison of different materials in terms of environmental impact has been analysed, for example, using fuselage segments [44–46], elevators [47], aircraft interior panels [48], and lightweight trolleys [49]. These studies, however, usually only look at individual life cycle phases or materials in order to propose specific process improvements. Thus, they can only be considered as comprehensive LCA to a limited extent as the interactions and interdependencies between different phases are not taken into account.

For a holistic LCA, however, it is important to consider and assess the aircraft in all life cycle phases. Due to the extensive scope of such studies, many are based on master's theses or dissertations. Johanning [50], for example, investigated the integration of an environmental impact assessment into the conceptual aircraft design phase. The author concluded that the operational phase has by far the largest environmental impact, caused mainly by fuel combustion. Similarly, Howe et al. [51] conducted an LCA of an Airbus A320, looking specifically at the manufacture, operation, and end-of-life to calculate the respective share of the total environmental impact. In this study, the operational phase accounted for 99 % of the total environmental impact, with no distinction made between maintenance and flight operations. The figures in this study are given in percentages only and do not provide exact numerical values. In 2006, Facanha & Horvath [52] calculated the environmental impact of a Boeing B747 freighter and compared the results with those of other means of transport. Not only was the entire life cycle of the vehicle considered, but also the construction and operation at the airport as well as fuel refining and distribution. In this study, however, only the inventory assessment was described in depth. The impact assessment was excluded from the study, resulting in a comparison of transport modes based only on air pollutants per freight activity. A similar approach

to comparing aviation with other modes of transportation was used by Chester [53], who compared an Embraer 145, a Boeing B737, and a Boeing B747, and by Cox [29, 54] (more details of this study can be found in the master's thesis by Jemioło [55]), assessing a variation of short-haul and long-haul aircraft, i.e., Short Narrow Body (SNB) and Large Narrow Body (LNB), representing the aviation sector. For the environmental assessment, the authors used an Economic Input-Output Life Cycle Assessment (EIO-LCA), which is a top-down approach that estimates the environmental impact based on economic activities [56], as the primary method leading to relatively high values. The reason for this is that the input-output approaches are rather approximate and usually contain wider system boundaries.

In a study by Lopes [57], a holistic LCA was carried out for an Airbus A330. The inventory for the manufacturing phase of the aircraft published in this master's thesis is used as a basis in many other studies. Another publication that is frequently referred to is that by Lewis [58], who compared three flight scenarios with different flight distances and aircraft types (Airbus A320, Airbus A330, and Airbus A380). The author considered aircraft manufacturing and operations using a hybrid approach combining Process-Based Life Cycle Assessment (P-LCA) and EIO-LCA. Jordão [59] applied an LCA study to the manufacturing, maintenance, and operational phases of an Airbus A330 and a Boeing B777 and compared these two aircraft types with each other. Noteworthy here is the relatively large ecological share of the maintenance phase of up to approximately 20 %, which was calculated on the basis of the energy consumption of the airport and electricity price. In a recently published study by Fabre et al. [28], an LCA of an Airbus A320 was carried out. The manufacturing of the aircraft, airport construction, as well as operations using different fuel types, were considered. Maintenance activities and end-of-life were, however, neglected due to a lack of data. The authors likewise concluded that LCA is a suitable tool for the evaluation of new technologies, such as hybrid-electric or hydrogen aircraft. The study by Schäfer [60] aimed to develop a life cycle sustainability assessment methodology for the aircraft pre-design comprising an environmental and an economic assessment. For this purpose, all life cycle phases, including maintenance and end-of-life, were assessed based on CO_2, nitrogen oxides (NO_X), and cumulated energy demand. In 2013, Dallara et al. [61] analysed the environmental impact of aircraft production and operations activities using a parametric Streamlined Life Cycle Assessment (S-LCA) tool called qUWick. The aircraft under consideration included an Airbus A320 and a Boeing B737 and were compared with LCA outcomes from the literature and existing EIO-LCA tools.

An overview of these mentioned LCA studies, whose outcomes are further applied as comparative values in Section 2.5, is provided in Table 2.1. Due to differences in aircraft types, additional information, such as aircraft weight or number of Passenger (PAX), is listed to normalise the results on a functional unit basis. The table furthermore provides information on the life cycle stages considered in each study as well as the applied LCA methods. These can mainly be categorised as a common P-LCA, an EIO-LCA, and a hybrid model combining these two approaches. An S-LCA is a simplified method that is particularly preferred for complex products. In this approach, often only individual impact categories are considered, for example, to compare different design options with each other. The studies by Howe et al. [51], Johanning [50], and Facanha & Horvath [52] are

excluded from the table due to missing numerical values. Similarly, only a small selection of aircraft types was considered from the publications by Cox [54] and Dallara et al. [61].

Table 2.1: Overview of comparable literature dealing with life cycle assessment of aircraft.

Study	**Chester** [53]	**Cox** [54]		**Lopes** [57]	**Lewis** [58]	**Jordão** [59]		**Fabre** [28]	**Schäfer** [60]	**Dallara** [61]
Aircraft Type	Boeing B737	SNB	LNB	Airbus A330	Airbus A320	Airbus A330	Boeing B777	Airbus A320	CeRAS	Airbus A330
PAX [-]	101	125	200	303	150	293	275	165	150	303
OEW [t]	37.1	31.0	51.0	124.4	42.1	106.2	134.8	37.2	42.1	124.4
Lifetime [years]	30	22	22	24	20	20	20	25	25	24
Manufacturing	●	●	●	●	●	●	●	●	●	●
Operations	●	●	●	●	●	●	●	●	●	●
Maintenance	●	○	○	○	○	●	●	○	●	○
End-of-Life	○	○	○	○	○	○	○	○	●	○
LCA Method	hybrid	P-LCA	P-LCA	P-LCA	hybrid	S-LCA	S-LCA	P-LCA	S-LCA	S-LCA

Note: ● included; ○ not included

In addition, a number of publications deal with the potential environmental impact of future aircraft concepts. These include hybrid-electric concepts [32], universal-electric powered concepts [62], or the use of SAFs [63, 64]. For these future technologies, a prospective LCA can be helpful for decision support in the design process or during engineering [65]. Johanning & Scholz [66], who compared electric, Liquid Hydrogen (LH_2), and SAF-powered aircraft, further indicated that additional renewable energy sources will be required to meet the increased energy demands of these concepts.

In summary, the environmental assessment of aircraft is currently an emerging topic. Most publications refer to the operational phase as by far the most influential phase of the entire life cycle. However, changes in operation, correlations, or other resulting dynamic effects cannot be adequately represented with the above-mentioned conventional LCA approaches. An extension of the classical LCA with, for example, a discrete-event simulation can enable a dynamic operating schedule for aircraft and can thus provide an even more detailed insight into the different life cycle phases and better represent technological effects.

2.2.2. Combination of Discrete-Event Simulation and Life Cycle Assessment

Discrete-event simulation consists of state variables that change at discrete points in time during a simulation and thus model and execute a process as a series of individual events [67, 68]. Advantages of discrete-event simulations include the ability to simulate complex systems wherein inputs and variables can be quickly exchanged to gain insight into their significance [69]. In addition, the simulated time can be easily varied and scaled without much effort. Due to the complex simulation setup, discrete-event simulations

have thus far rarely been used for environmental issues [70]. However, according to Thiede et al. [71], a combination of LCA and discrete-event simulation is an effective solution that can overcome some of the problems of classical LCA, such as its static and disregard behaviour. Since there are no publications in the field of aviation dealing with a combination of LCA and discrete-event simulation, studies from other industrial sectors are considered in this section.

The authors de Oliveira Gomes et al. [72] compared the environmental impact of different fuels for forklift trucks in a production facility. Thereby, discrete-event simulation and LCA were carried out consecutively. The discrete events contained input data such as fuel type and consumption or the amount of products handled by the forklifts and were used to simulate different scenarios. After this simulation, the results were then used to perform an LCA by adopting the GWP. A similar approach was followed by Bengtsson et al. [73], who analysed the energy and GHG emissions of Boeing machine tools to achieve benchmarks for sustainable manufacturing. The discrete-event simulation was performed with input data, such as cycle, setup, and downtimes for the machining tools. The results of the discrete-event simulation were then evaluated in an LCA focusing on direct and indirect energy consumption, CO_2 emissions, and NO_X emissions. Muroyama et al. [74] integrated discrete-event simulation input data into an LCA simulation to assess the environmental impact of a golf ball factory. Discrete parameters included the number of machines, type of polymer, and number of repair workers. The result of this simulation then provided the energy and material consumption, CO_2 emissions, and flow rate. The approach provided more effective resource management in the production process, but the authors were faced with large uncertainties due to the lack of LCI data. Comparable approaches were used, for example, by Sproedt et al. [75] to optimise the operational management of a factory, by Andersson [76] to analyse the material and energy consumption of an assembly line production, and by Löfgren & Tillman [77] to weight decision-making processes in a manufacturing process. These studies have in common that discrete-event simulation and LCA were carried out independently of each other. The results of the discrete-event simulation were hereby used as a basis for the LCA, with no possibility to intervene in the simulation itself due to ecological factors.

Apart from these sequential approaches, discrete-event simulation and LCA can be used simultaneously to enhance a combined model. Johansson et al. [78] focused on alternative solutions for a juice production plant. Using a discrete-event simulation enriched with LCA data, several factory configurations with different numbers of tanks and batches were compared. Each time an event was triggered, an LCA was automatically performed and the resulting environmental values instantly updated the model's output parameters. The focus of this study was to compare the carbon dioxide equivalents (CO_2-eq.) of the factory settings. The authors concluded that combining discrete events with LCA was much more time-efficient than applying independent analyses. A similar approach was used by Sigurðardóttir et al. [79] examining cod fishing in Iceland with a focus on the comparison of different vessel types. Each fishing activity represented a discrete event that was automatically updated with environmental impact parameters (e.g., CO_2 of the vessels) from an LCA. This allowed the environmental impact model to be traceable and easily scalable. In addition to these publications focusing mainly on the production and manufacturing phases of products, a study by Barletta et al. [80]

addressed the management of electronic waste. In this context, different sorting methods were evaluated in order to obtain real-time data on energy consumption. Widok et al. [81] created a joint model for discrete-event simulation and material flow analysis, which was linked to environmental impact data to analyse different scenarios for manufacturing processes. The advantages mentioned here are again the possibility for precise analyses as well as simple and rapid adjustments of input data. Other publications have focused on construction processes in the building sector and examined the environmental impact of construction machinery and equipment [82, 83] as well as the environmental performance of supply chains and on-site equipment [84].

Based on this literature review, a simultaneous approach was chosen for the present study in order to ensure a realistic variation in life cycle simulation based on ecological impacts. The methodology presented in the following sections is able to simulate an aircraft's life cycle in detail and environmentally assess it with the help of an LCA.

2.3. Description of Discrete-Event Simulation

The combination of LCA and discrete-event simulation described in this chapter is based on an existing and generic Life Cycle Cash Flow Environment (LYFE) [85]. This modular framework was developed by the DLR Institute of Maintenance, Repair and Overhaul and provides a detailed simulation of the aircraft economic life cycle and the assessment and analysis of changes throughout the aircraft's operation. This chapter provides a more detailed introduction to the LYFE simulation environment (Section 2.3.1), describes the aircraft characteristics of the applied use case (Section 2.3.2), and presents the flight and maintenance schedule needed for the simulation of the operational phase (Section 2.3.3). The latter serves as the foundation for the subsequent ecological assessment of the aircraft over all life cycle phases.

2.3.1. Introduction to LYFE

So far, LYFE's main focus has been the economical cost-benefit evaluation of an aircraft over its entire life cycle. Thereby, all relevant cash flows (costs as well as revenues) are captured and analysed to obtain information on the profitability of the aircraft and its operator. The core of LYFE is the creation of an event calendar for the given aircraft, which covers all relevant events in the aircraft's life cycle, including aircraft purchase, performed flights, scheduled and, if necessary, unscheduled maintenance events, monthly recurring costs, as well as the sale of the aircraft at the end of its life. These specific events, particularly during operation, are processed sequentially according to a flight and maintenance schedule, resulting in a steadily growing event calendar over the duration of the simulation. Figure 2.1 shows an extract of the event calendar for a short-range aircraft with performed flights (blue) and maintenance events (green). Each event is an object with defined attributes depending on the event type. In general, all event types contain a unique timestamp and a specific duration that define the course of the event. Further event type-dependent parameters include the departure and arrival airport of a flight event including distance, fuel consumption, and related costs. For maintenance events, a distinction is made between the maintenance type (line, base, and shop maintenance)

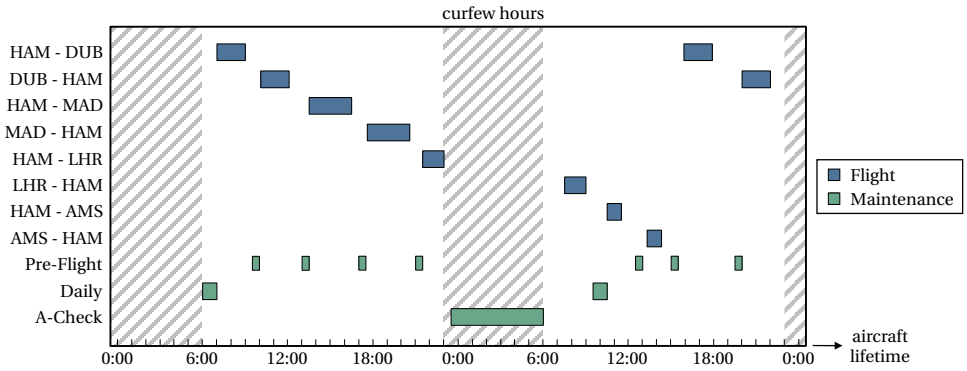


Figure 2.1: Operating schedule for two days including flight and maintenance events (based on [85]).

and the associated tasks. Boundary conditions such as turnaround times or curfew hours at certain airports are also taken into account.

The structural design of LYFE enables the analysis of primary as well as secondary effects during the service life. Primary impacts are those that directly affect flight operations, whereas secondary impacts result from a more complex interaction network. For example, a modification to the aircraft may lead to a reduction in fuel consumption and thus has a direct impact on fuel costs and flight emissions (primary). However, maintenance activities associated with this modification may increase the ground time of the aircraft (secondary), which in turn may have implications for the operator.

Within the scope of this study, the economic focus of LYFE is expanded to include an LCA with ecological factors by performing an environmental assessment for each event or event type depending on its event-specific parameters. For instance, the ecological impact for each flight is calculated individually based on the flown distance, the number of PAX (depending on the aircraft seating and load factor), and the fuel consumption. The same applies for individual maintenance or modification events. Thus, each event is assigned an individual ecological impact, which is saved as an attribute, similar to those for costs. The generic extension with ecological factors thus enables optimisation of aircraft operations according to both economic and ecological aspects.

2.3.2. Aircraft Characteristics

The environmental extension of LYFE is exemplary applied to an Airbus A320 type of aircraft. The main aircraft characteristics, which are especially necessary for the environmental assessment and the simulation of the life cycle, are hereby taken from the project Central Reference Aircraft data System (CeRAS) [86]. CeRAS provides a variety of operational parameters, such as the design range or the possible number of PAX. In addition, the detailed mass breakdown at the system-level is particularly beneficial for the consideration of the manufacturing and end-of-life phase of the aircraft. The service life of the aircraft is assumed to be 25 years and it is powered by two conventional CFM56-5B engines and Jet A-1 fuel. An overview of the relevant characteristics of the aircraft can be found in Table 2.2.

Table 2.2: CeRAS aircraft characteristics (based on [86]).

Parameter	Unit	Value
Design Range	NM	2,750
Cruise Mach Number	-	0.78
Passenger Capacity	PAX	150
Average Load Factor	%	80
Operating Years	years	25
Operating Empty Weight	kg	42,100
Manufacturer's Empty Weight	kg	38,200
Maximum Fuel Weight	kg	18,700
Engine Type	-	CFM56-5B
Number of Engines	-	2
Fuel Type	-	Jet A-1

2.3.3. Flight and Maintenance Schedule

The life cycle simulation is based on a flight and maintenance schedule for an Airbus A320 with the above-mentioned characteristics. Table 2.3 gives an extract of the exemplary flight plan and was created based on real flight operations of this aircraft type performed by different operators. Thereby, socio-economic air traffic forecasts, including airport capacity, aircraft performance data, and different flight routes were considered to simulate a real-world fleet utilisation. The flights are mainly short-haul with occasional medium-haul flights, resulting in an average utilisation rate of about four Flight Cycles (FCs) per day and an average flight duration of one and a half FHs. Each flight is identified by a start and end time, including departure and arrival airport. In addition, the consumed fuel, as well as the flown distance, are indicated. Figure 2.2 illustrates the route network operated by the aircraft. The flight schedule was created as part of the EXACT project and a more detailed description of the creation of the flight plan can be found in Wehrspohn et al. [87].

Table 2.3: Extract from the flight schedule of an Airbus A320 with additional information on flight duration, distance, and fuel burn.

Origin	Destination	Duration [h:mm]	Distance [km]	Fuel Burn [kg]
Amsterdam (AMS)	Lisbon (LIS)	2:27	1,848	5,434
Lisbon (LIS)	London (LHR)	2:05	1,566	4,720
London (LHR)	Berlin (TXL)	1:16	948	3,166
Berlin (TXL)	Zurich (ZRH)	0:53	660	2,451
Zurich (ZRH)	Hamburg (HAM)	0:56	694	2,533

The maintenance schedule is based on a maintenance analysis of the Airbus A320 family from Aircraft Commerce [88] and consists of different categories, comprising line,



Figure 2.2: Illustrated route network of the flight schedule performed by an Airbus A320 [87].

base, and shop maintenance. Line maintenance checks are rather short and include mainly visual inspection tasks and oil or hydraulic fluid changes. Base maintenance checks, on the other hand, take much longer and are usually carried out during layovers and in a hangar. Large components, such as the engine or landing gear, are thoroughly inspected and overhauled in special shop visits. For these shop visits, the components are dismantled from the aircraft and transported to a special workshop. Meanwhile, the aircraft usually receives a replacement component to continue flight operations. Table 2.4 summarises a simplified version of the Airbus A320 maintenance schedule with associated downtimes and task intervals in FCs, FHs, or days. With these intervals, the corresponding maintenance events are integrated into the flight plan before one of these thresholds expires at the latest.

Table 2.4: Simplified maintenance schedule of an Airbus A320 (based on [88]).

Name	**Type**	**Downtime** [hours]	**Interval Thresholds** [FH]	[FC]	[days]
Transit	Line	0.5	0	1	0
Pre-Flight	Line	1	0	0	1
Daily	Line	1	0	0	1.5
Weekly	Line	2	0	0	7
A	Line	10	450	0	100
C1	Base	68	4,200	0	540
…	…	…	…	…	…
C16	Base	799	67,200	0	540
Engine	Shop	1,008	10,000	8,300	0
Landing Gear	Shop	1,008	28,000	18,350	3,652
APU	Shop	504	5,500	4,600	0

2.4. Life Cycle Assessment

The following section describes the approach of the implemented LCA, which is used to support the ecological extension of LYFE. After an initial goal and scope definition (Section 2.4.1), the preparation of the LCI (Section 2.4.2) is presented. Section 2.4.3 then provides more information on the chosen LCIA methodology and its associated impact categories.

2.4.1. Goal and Scope Definition

In the goal and scope phase, the overall aim of the study as well as the assumptions and limitations are described. This is usually carried out before any data are collected and serves as the basis for the subsequent LCA steps. According to ISO 14040 [21], the objective of the study states the intended application, the reason for carrying out the study, or whether the results should be used for comparative purposes. The scope rather describes the product system of the study, including its function, system boundaries, the assumptions and limitations, as well as any data quality requirements. Additionally, one or more functional units must be selected to further describe the product system of the study in more detail and to provide a reference for future comparisons.

2.4.1.1. Study Goal

The goal of this study is a detailed holistic LCA of an aircraft similar to an Airbus A320 and to subsequently compare it with other literature findings. In particular, the operational phase is simulated with the help of a discrete-event simulation using the flight and maintenance schedule described in Section 2.3.3, thus providing a detailed basis for a thorough ecological assessment.

2.4.1.2. System Boundary

The analysed life cycle phases include the manufacturing, flight operations, maintenance, and end-of-life of the aircraft. In particular, the ground-based phases (production, maintenance, and end-of-life) are considered and calculated in detail. A graphical representation of the system boundaries is presented in Figure 2.3.

In the manufacturing phase, raw material extraction, as well as manufacturing and assembly processes, are within the scope of the study. In addition, the transport of components from different manufacturing sites (similar to that of an Airbus A320) to the Final Assembly Line (FAL) is considered. Construction, maintenance, and operation of the manufacturing facilities are not included in this study. The flight operations include the production and transport of kerosene as well as the emissions resulting from combustion in flight. For the maintenance activities, equipment, materials, spare parts, transportation, and facilities are included in the system boundaries. The end-of-life of the aircraft ends with the selection and transportation to different end-of-life scenarios (landfill, incineration, recycling, or re-utilisation). Airport infrastructure, such as terminals, runways, and ground facilities, is not included in the system boundaries.

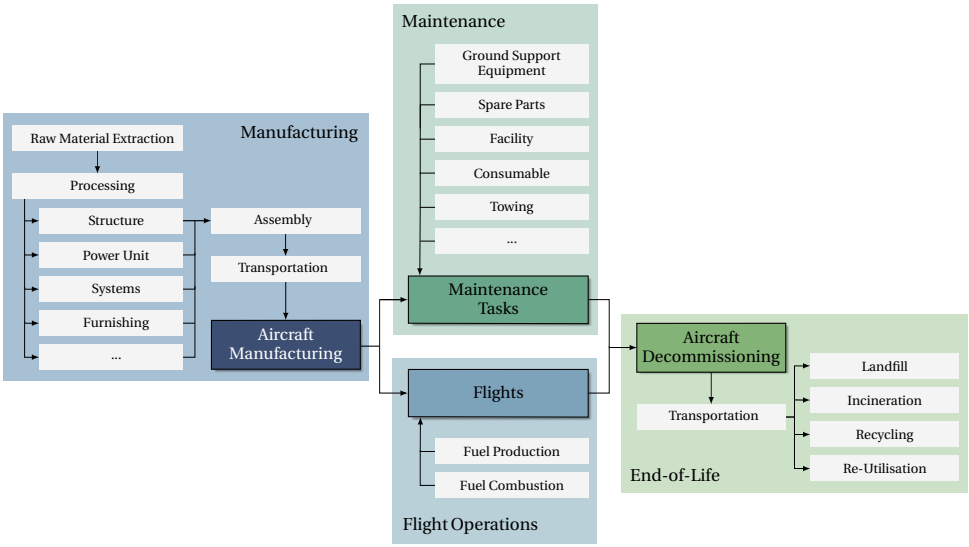


Figure 2.3: System boundaries of the presented LCA study.

2.4.1.3. Functional Unit

The functional unit is important for the interpretation and quantification of the LCA results. A very commonly used functional unit for aircraft in the literature is the unit per ASK. By choosing this unit, it can be ensured that the results of the calculations can be compared with other LCA studies, regardless of the chosen lifetime or the aircraft's utilisation. It is, however, dependent on the seating of the aircraft, as the flown kilometres are divided by the number of seats. Another option for the functional unit is the per Operating Empty Weight (OEW). This unit is particularly useful for comparing manufacturing and end-of-life processes, as these take place only once in a lifetime, irrespective of the operations phase, and are dependent on the aircraft weight. For the comparison with other literature findings (Section 2.5), both functional units are used, depending on each life cycle phase.

2.4.2. Life Cycle Inventory

The LCI analysis is essential for the implementation of an LCA. The inventory consists of inputs, e.g., resources and outputs, such as emissions (to air, water, and soil), waste, or other products. These inputs and outputs are summarised as flows and form processes that are linked to each other through exchanges of these flows. For the compilation of the inventory, the ecoinvent 3.7.1 cut-off database and several additional publications were used. A description of the LCI preparation for the different life cycle phases can be obtained below. An overview of the inventory can further be found in the supplementary data.

2.4.2.1. Manufacturing

Aircraft design and the associated manufacturing phase have a high level of complexity and thus a high potential for efficiency improvements for future aircraft. To gain an understanding of specific production stages and their current environmental impact, a detailed and component-based inventory is important. The manufacturing phase is divided into three sections: raw material extraction, processing and assembly, and transportation.

Raw Material Extraction

For the creation of the LCI in the manufacturing phase of the aircraft, a detailed mass and material breakdown at the component-level is required. For this purpose, the aircraft under consideration must first be broken down into its structure and systems in order to consider them individually. An overview of the aircraft components and considered sub-components is shown in Figure 2.4.

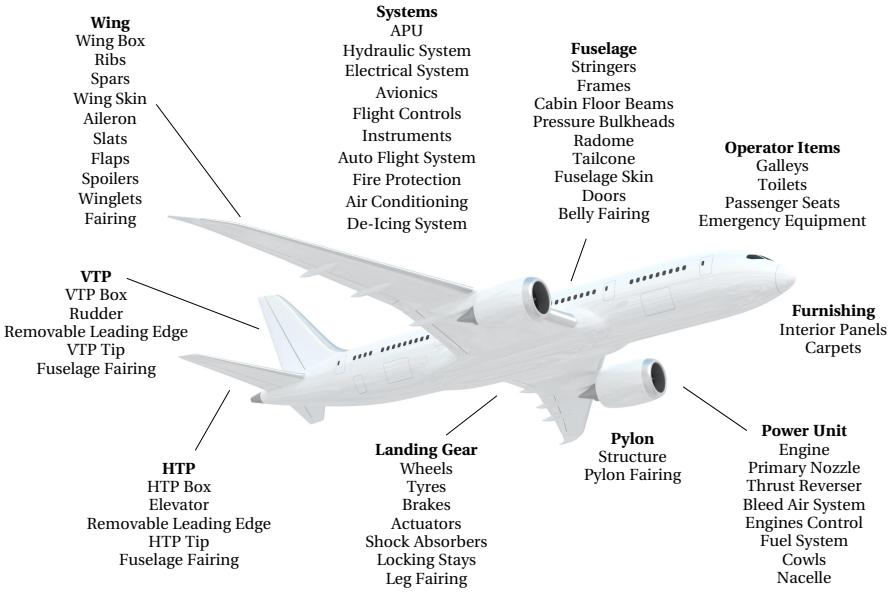


Figure 2.4: Component breakdown of the aircraft for the manufacturing LCI.

The aircraft structure comprises the wings, fuselage, Horizontal Tail Plane (HTP), Vertical Tail Plane (VTP), landing gear, and pylons with their respective compounds. Engines with nacelle, bleed air system, as well as the entire fuel system are counted as part of the power unit, whereas the systems category includes all other flight-relevant equipment. In addition, the mass breakdown for structure and system components is taken from CeRAS, as the values are comparable to those of an Airbus A320. Figure 2.5 illustrates the OEW distribution among the structure, systems, power unit, operator items, and furnishing. The aircraft structure accounts for about 58 % of the aircraft weight, followed by the power unit with 19 %.

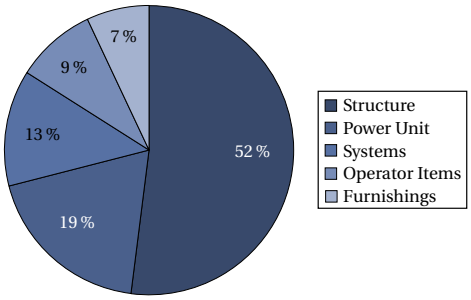


Figure 2.5: Mass breakdown of the considered aircraft based on CeRAS and own calculations and assumptions.

The structural components are assigned to one or more corresponding materials. For this, a variety of publications is used as a basis and, where necessary, adjusted with appropriate estimates. In the case of the wing, for example, the spars, ribs, and wing skin are mainly made of aluminium, resulting in a total material content of about 85 % [89]. Other structural elements, such as ailerons, winglets, or fairings for landing gear or flap tracks are made of Carbon Fibre-Reinforced Plastic (CFRP) [90]. In addition, some components of the aircraft, such as the belly fairing or the VTP leading edge, are made of Aramid Fibre-Reinforced Plastic (AFRP) and Glass Fibre-Reinforced Plastic (GFRP). As the ecoinvent database does not contain these material datasets, CFRP is assumed for these components as well. For the power unit, a material and mass breakdown from Lopes [57] was used as a basis and expanded with an EASA Type-Certificate Data Sheet [91]. Based on these assumptions, the most commonly used materials in the engine are titanium (27 %), which is, for instance, used for the turbine blades, CFRP (19.5 %), mainly applied for nacelle and cowls, as well as nickel (17 %), which is used under high operating temperatures in the engines due to its considerable strength and corrosion resistance [92]. The material breakdown for the systems is subject to many uncertainties and assumptions. By using product data sheets and a variety of other publications, materials and weights are assigned to each individual system component. Aluminium, steel, and copper are identified as the most common materials for system components. An overall breakdown of the materials used in the aircraft can be seen in Figure 2.6 and is confirmed with data from the literature.

The calculation of the elementary flows from raw material extraction $EF_{extraction}$ at the component-level is carried out using Equation (2.1), where $EF_{material}$ represents the elementary flows associated with the extraction of material M, and m is the mass of component C.

$$EF_{extraction,C} = \sum_{M} EF_{material,C,M} \cdot m_{C,M} \tag{2.1}$$

Processing and Assembly

Manufacturers usually keep the manufacturing processes in aircraft construction highly confidential in order to maintain their competitiveness. To estimate the respective manu-

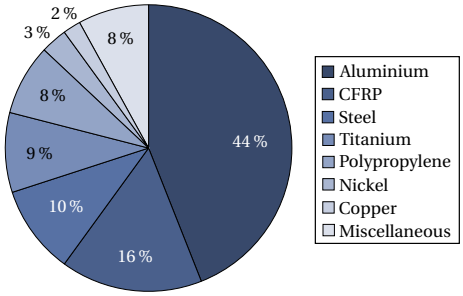


Figure 2.6: Material breakdown of the considered aircraft based on CeRAS and own calculations and assumptions.

facturing process, precise knowledge of the component geometry is needed, which is not feasible within the scope of this study. For this reason, an average value for the processing energy consumption was used for each material, regardless of the specific component. Aluminium sheets for the wing skin, for example, have to be milled in shape and hardened through various heat treatment processes before utilisation. The processing of one kilogram of aluminium is assumed to have an energy consumption of 89.3 MJ/kg [93]. For the manufacturing of CFRP components, several processes, including fibre winding, tape laying, and injection moulding can be applied. Based on a study by Bohlender [93], an energy consumption value of 40.2 MJ/kg is therefore selected. For titanium, a significantly higher energy consumption of on average 216 MJ/kg was reported in the literature [94, 95], as very high amounts of specific energy inputs are required, e.g., for milling or machining, due to titanium's poor thermal conductivity properties. For each component, the corresponding elementary flows $EF_{processing}$ are calculated based on the energy consumption during processing $E_{processing}$ and its specific material composition.

$$EF_{processing,C} = \sum_{M} E_{processing,C,M} \cdot m_{C,M} \tag{2.2}$$

For the elementary flows associated with assembly $EF_{assembly}$, material-specific joining methods were determined. For metallic materials such as aluminium, possible joining methods include rivets or screws. CFRP, on the other hand, is often assembled via adhesive bonding. The energy consumption for the assembly $E_{assembly}$ is 23.8 MJ/kg for metals and 14.2 MJ/kg for CFRP components.

$$EF_{assembly,C} = \sum_{M} E_{assembly,C,M} \cdot m_{C,M} \tag{2.3}$$

Transportation

As this study focuses on an aircraft similar to an Airbus A320, the transport between different production sites is included in this environmental assessment. For this purpose, all distributed components must first be identified and assigned to a suitable transportation

vehicle V. The ecoinvent database contains a number of different datasets for calculating the elementary flows associated with transportation $EF_{transportation}$ of a given component, depending on its mass m and the distance travelled d (see Equation (2.4)). This study assumes that the FAL is located in Hamburg, Germany. The wings are manufactured in the UK and in Germany, while for the fuselage, some parts are manufactured in France whereas others are fabricated directly at the FAL. Within Europe, the Airbus A330-700L (also known as Beluga [96]) and trucks are the main means of transport.

$$EF_{transportation,C} = \sum_{V} EF_{transportation,C,V} \cdot m_{C,V} \cdot d_{C,V} \tag{2.4}$$

The total inventory of aircraft manufacturing is then calculated as the sum of raw material extraction, processing, assembly, and transportation for all considered components C.

$$EF_{manufacturing} = \sum_{C} (EF_{extraction,C} + EF_{processing,C} + EF_{assembly,C} + EF_{transportation,C}) \tag{2.5}$$

2.4.2.2. Flight Operations

The inventory of flight operations depends on the aircraft's specific fuel consumption, the distance flown, and the number of completed flights. A distinction can be made between the production of the fuel and the effects and emissions during combustion in flight. These two factors are taken from the literature and database information and are discussed in more detail below.

Fuel Production and Supply

Jet A-1 kerosene is mainly used in aviation for a variety of different turbine-powered aircraft and must meet strict international regulations. The fuel is mainly produced from crude oil and must go through various production processes. These include, for example, extraction through drilling. The crude oil is then broken down into its constituents by distillation, purified, and finally processed for transportation and utilisation [97]. According to Koroneos et al. [98], the refining process is the most environmentally harmful operation due to its highly energy-intensive process. Depending on the region, crude oil source, and refinery process, the environmental impact of the fuel production can vary greatly. Various studies have calculated the carbon intensity of the whole kerosene production process to be 12-22 gCO_2-eq./MJ [99]. With a specific energy value of 43.2 MJ/kg [63], this results in 0.5-0.95 $kgCO_2$-eq./kg fuel. These values are consistent with the ecoinvent database for the *market for kerosene* dataset, which includes kerosene production and supply, and is therefore used as a basis for this assessment.

Flight Emissions

Emissions emitted during the flight phase account for the main part of the ecological impact of aircraft in all the considered LCA studies. For a detailed calculation of the climate

impact, not only CO_2 emissions but also so-called non-CO_2 climate effects have to be taken into account. The most common non-CO_2 effects are caused, for example, by the production of water vapour, NO_X emissions, or Contrail-Induced Cloudiness (CIC) [100]. Unlike CO_2 emissions, which are location-independent because of their long lifetime in the atmosphere, these effects are strongly correlated with altitude and geographical longitude and latitude. Due to this complexity and the fact that there is no direct linear dependency between overall climate impact and fuel consumption, there are significant uncertainties in the ecological calculation of aircraft emissions [101]. There are already existing frameworks and studies (e.g., by Grewe & Stenke [102]) that incorporate all these parameters and thus provide a detailed and reliable statement on the climate impact of aviation. However, the results of these calculation tools are often limited to a few climate-related impact categories, such as GWP or Average Temperature Response (ATR), even though non-CO_2 emissions may also affect other environmental impact beyond CC. For a holistic LCA analysis, as is the aim of this study, the GWP alone is not sufficient. Therefore, a simplified approach is chosen in this study to at least consider the magnitude of flight operations, while non-CO_2 climate effects are not assessed explicitly.

The ecoinvent database provides ecological datasets for the *market for transport, passengers, aircraft* over a certain distance. These datasets are divided into very short-haul (< 800 km), short-haul (800-1,500 km), medium-haul (1,500-4,000 km), and long-haul flights (> 4,000 km). The distinction in these categories can be explained by the fact that, for example, short-haul flights are particularly harmful per ASK, as the emissions during the kerosene-intensive climb phase are exceedingly high [103]. A closer look at the ecoinvent dataset, however, reveals that these datasets proportionally include both the production and transport of kerosene and the construction and operation of the airport. Due to the lack of data availability on the flight phase of aircraft and their environmental impact, the corresponding activities that lie outside the system boundaries of this study and that are already covered in fuel production are removed from every impact category. The high complexity of the interconnection between individual inventory datasets entails further uncertainties that have to be critically discussed in the analysis and interpretation of the results.

The inventory of the operation phase is thus derived from the modified ecoinvent transportation dataset ($EF_{PAX\text{-}transport}$) as a function of the flight distance d and the number of PAX n_{PAX}, as well as from the elementary flows associated with kerosene production $EF_{kerosene}$, which depend on the amount of burned fuel m_{fuel} per flight F.

$$EF_{operation} = \sum_{F} (EF_{PAX\text{-}transport,F} \cdot d_F \cdot n_{PAX,F} + EF_{kerosene,F} \cdot m_{fuel,F}) \tag{2.6}$$

2.4.2.3. Maintenance

Maintenance is very often neglected or simplified in LCA studies. However, due to the event-based nature of this environmental assessment, independent consideration of each maintenance event in the maintenance schedule (see Section 2.3.3) is essential. For this purpose, the activities in each check are analysed and modelled according to their

specific boundary conditions. The most important factors for the ecological assessment of maintenance activities are:

- The manufacturing and transportation of spare parts;
- The energy consumption of maintenance equipment;
- The operation of the maintenance facilities.

In particular, the latter two aspects are strongly dependent on the duration of the respective check. For simplification, the existing maintenance activities listed in the maintenance schedule (as presented in Table 2.4) are divided into line, base, and shop maintenance.

Line Maintenance

Line maintenance includes the maintenance work that must be carried out before a flight to ensure the airworthiness of the aircraft. This usually includes pre-flight, transit, daily, weekly, and A-checks [104]. Short and frequent maintenance tasks, such as pre-flight checks and transit checks, usually only involve visual checks directly on the ramp. As this is assumed to be carried out by the aircraft crew and thus no transport or special equipment is involved, the elementary flows for these tasks are neglected. Other line maintenance checks include activities that cause, for instance, emissions generated by Ground Support Equipment (GSE), maintenance vehicles, or general service tasks, such as engine oil servicing. Equation (2.7) defines the line maintenance inventory EF_{line} for each maintenance task T based on the elementary flows associated with the equipment EF_{GSE}, the vehicles $EF_{vehicle}$, and the consumables $EF_{consumable}$.

$$EF_{line} = \sum_{T} (EF_{GSE,T} + EF_{vehicle,T} + EF_{consumable,T}) \tag{2.7}$$

Base Maintenance

The maintenance schedule presented in Section 2.3.3 comprises various C-checks, which are characterised by a high level of detail and a comparatively long duration [104]. During the C-check, safety-relevant systems and components are checked in detail. In addition, intensive cleaning and an overhaul of the cabin are carried out [105]. For base maintenance, the aircraft usually has to be transferred to a maintenance base, where the maintenance work is performed in a hangar. Using data from the literature [106], energy consumption for the hangar per hour (for lighting, heating, or ventilation) was calculated related to the aircraft size [107]. The inventory of base maintenance EF_{base} is similar to that of line maintenance (see Equation (2.7)), with the additional elementary flows of operating the facility EF_{hangar} and towing of the aircraft EF_{towing}.

$$EF_{base} = \sum_{T} (EF_{line,T} + EF_{hangar,T} + EF_{towing,T}) \tag{2.8}$$

Shop Maintenance

Certain complex components, such as the engine, landing gear, and the APU, are replaced during the course of the aircraft's life to be thoroughly overhauled. The aim of so-called shop visits is to detect corrosion, fractures, or other defects that are not visible during a regular line or base check [104]. Therefore, the components are first removed from the aircraft and transported to a special workshop. There, they are disassembled, cleaned, stripped of paint, if necessary, and then examined via non-destructive testing methods using special equipment. Information on the quantity of replaced sub-components (i.e., scrap rate) is very difficult to obtain. Based on an article by Aircraft Commerce [108], stating that 25 % of engine shop visit costs are related to spare parts, this assumption has been adapted to the environmental perspective. It is therefore assumed that one quarter of the respective shop components needs to be fully replaced. For the inventory modelling, the energy consumption of the workshop is determined similarly to that of the hangar. The transport from the aircraft to the workshop is calculated using the component mass and the travelled distance. An important environmental aspect of the engine's workshop visit is a final engine test run in a test cell, where the engine is operated in different modes for several minutes to ensure full operational capability. The inventory of the shop visit EF_{shop} is calculated using Equation (2.9) and workshop operation ($EF_{workshop}$), special workshop equipment ($EF_{equipment}$), the manufacturing of spare parts (EF_{spare}), testing procedures ($EF_{testing}$), and the transportation to the workshop itself ($EF_{transportation}$).

$$EF_{shop} = \sum_{T} (EF_{workshop,T} + EF_{equipment,T} + EF_{spare,T} + EF_{testing,T} + EF_{transportation,T}) \quad (2.9)$$

In addition to these mentioned maintenance categories, there are other recurring tasks that may also influence the environmental impact. These include, for example, the regular replacement of tyres and brakes or engine washes, as further explained in Rahn et al. [109]. However, these maintenance tasks are considered as non-scheduled tasks and are therefore not included in the inventory of this study.

2.4.2.4. End-of-Life

The final phase after the aircraft's service life is the end-of-life. Typical end-of-life scenarios are landfill, incineration, recycling, or re-utilisation, although there is very little information on the disposal scenario for individual aircraft components. The most comprehensive study in this area to date was carried out as part of the Process of Advanced Management of End-of-Life of Aircraft (PAMELA) [110] project, a joint study by the EU and aircraft manufacturers. The results of this study are applied as a basis for this end-of-life assessment, albeit individually adjusted. For example, the distribution of end-of-life scenarios for structural components, such as wings, fuselage, HTP, and VTP, is taken from the PAMELA study. However, own assumptions were made for the landing gear and engine. Due to their high residual values and the fact that they are subject to regular overhauls during their lifetime, a certain re-use factor of 75-80 % is assumed for these components.

For the systems, on the other hand, it is more difficult to find adequate information, which is why the end-of-life treatment is estimated individually based on the material scarcity. For small parts, such as heat exchangers or electrical and hydraulic valves, a landfill rate of 100 % is assumed, while the APU, batteries, or flight control actuators are considered to be partly recycled or re-used. An overview of the proportion of the individual end-of-life scenarios for the entire aircraft based on the mass is shown in Figure 2.7. Landfill and recycling each account for the largest share of the aircraft end-of-life, namely 34 % and 41 %, respectively, whereby only 12 % of the total aircraft is directly re-used.

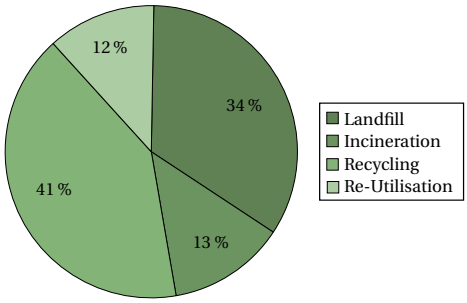


Figure 2.7: Distribution of the end-of-life scenarios of the entire aircraft based on the aircraft weight.

After creating an individual disposal scenario for each component, the respective environmental consequences of these scenarios are calculated. For instance, if a component is sent to a landfill, no impact was assumed except for the transportation to this landfill site. Incineration, on the other hand, is considered a possible waste-to-energy method, which can be used to generate energy in the form of electricity and heat by burning the waste. Depending on the material, incineration can generate up to 44 MJ/kg, which has a positive effect on the overall environmental impact of the aircraft. The elementary flows of the incineration scenario $EF_{incineration}$ are calculated with Equation (2.10), where $E_{incineration}$ is the energy generated from incinerating a material.

$$EF_{incineration,C} = \sum_{M} E_{incineration,C,M} \cdot m_{C,M} \tag{2.10}$$

Significantly more benefits can be created by the recycling of components, as energy can be saved, and water, soil, and air pollution can be reduced by proper treatment [111]. A so-called credit for avoided virgin production was assumed for the proportion of recyclable material. This assumes that the recycled material of a given product substitutes virgin material for future products [112]. Equation (2.11) is used to calculate the inventory of recycling a component $EF_{recycling}$. Since the energy of a recycled material $E_{recycling}$ is usually lower than that of the virgin material E_{virgin}, the energy consumption of the recycling process is usually negative. $\eta_{recycling}$ is the specific recycling rate of a component.

$$EF_{recycling,C} = \sum_{M} (E_{recycling,C,M} - E_{virgin,C,M}) \cdot \eta_{recycling,C,M} \cdot m_{C,M} \tag{2.11}$$

Re-utilisation assumes that a component can be re-used without further processing. In this calculation, a specific re-utilisation efficiency $\eta_{re\text{-}utilisation}$ of 90 % is assumed. This means that 10 % of the original energy is necessary due to, for instance, a new recertification or minor adjustments. With Equation (2.12), the elementary flows associated with component re-utilisation are calculated.

$$EF_{re\text{-}utilisation,C} = \sum_{M} E_{virgin,C,M} \cdot \eta_{re\text{-}utilisation,C,M} \cdot m_{C,M} \tag{2.12}$$

In addition to these calculations, it is assumed that for each component, transportation ($EF_{transportation}$) is required for the respective end-of-life scenario, either to the landfill, incineration site, or back to the manufacturer or operator for re-utilisation. The total inventory of the aircraft end-of-life EF_{eol} is calculated as:

$$EF_{eol} = \sum_{C} (EF_{incineration,C} + EF_{recycling,C} + EF_{re\text{-}utilisation,C} + EF_{transportation,C}) \tag{2.13}$$

2.4.3. Life Cycle Impact Assessment

The LCIA is the third step of the LCA in which the elementary flows from the LCI are transferred into their potential impact on the environment [34]. For this purpose, the in- and outputs of the LCI are assigned to various impact categories, e.g., Climate Change

Table 2.5: Impact categories for the LCIA (taken from [113]).

Abbr.	Impact Category	Indicator	Unit
CC	Climate Change	Global Warming Potential	kg CO_2-eq.
AP	Acidification	Accumulated Exceedance	mol H^+-eq.
FETP	Freshwater Ecotoxicity	Comparative Toxic Unit for Ecosystems	CTUe
FEP	Freshwater Eutrophication	Fraction of Nutrients Reaching Freshwater End Compartment (P)	kg P-eq.
MEP	Marine Eutrophication	Fraction of Nutrients Reaching Marine End Compartment (N)	kg N-eq.
TEP	Terrestrial Eutrophication	Accumulated Exceedance	mol N-eq.
HHC	Carcinogenic Effects	Comparative Toxic Unit for Humans	CTUh
IR	Ionising Radiation	Human Exposure Efficiency	kBq U^{235}-eq.
ODP	Ozone Depletion Potential	Ozone Layer Depletion	kg CFC-11-eq.
POF	Photochemical Ozone Formation	Tropospheric Ozone Concentration Increase	kg NMVOC-eq.
PM	Particulate Matter	Human Health Effects Associated with Particulate Matter	disease incidences
WS	Water Use	User Deprivation Potential	kg world eq. deprived
ECF	Energy Carriers	Abiotic Resource Depletion	MJ
LU	Land Use	Soil Quality Index	m^2a
MM	Minerals and Metals	Abiotic Resource Depletion	kg Sb-eq.

(CC), ODP, AP. These impact categories must first be selected for the respective LCA and usually concern the three areas: natural environment, human health, and natural resources. In this study, the Environmental Footprint (EF) 2.0 methodology [113] was chosen as LCIA methodology. Table 2.5 lists the impact categories of this methodology as well as their indicators and units. The material and energy inputs and outputs are first assigned to one or more associated impact categories. The subsequent characterisation evaluates the contributions of the inputs and outputs in the respective impact categories. For this purpose, so-called characterisation factors are used with which the emission impacts are multiplied. Two further optional steps are weighting and normalisation of the categories [114]. The LCIA is usually carried out automatically with appropriate LCA software. In this study, the open-source and python-based LCA framework Brightway2 is applied to perform the LCIA.

2.5. Results

In the following, the LCA results for all considered life cycle phases are presented. Due to the study boundary conditions and different functional units, the comparison with the literature is carried out separately for each life cycle phase (Section 2.5.2). This is followed by a brief interpretation of the results (Section 2.5.3) and, based on this, the strengths and weaknesses using discrete-event simulation are discussed (Section 2.5.4).

2.5.1. Total Results

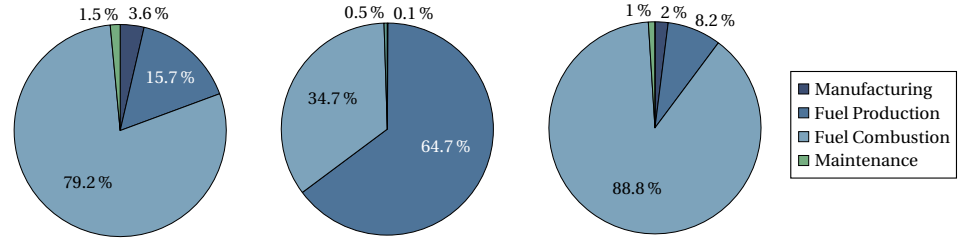
At the end of the discrete life cycle simulation, all events are summarised according to their respective life cycle phase. Table 2.6 provides an overview of the calculated values in the impact category CC. The results are given in absolute values and normalised per ASK, as well as in their respective percentage share, of the life cycle. Considering the environmental impact of the aircraft over 25 years, the flight phase has, by far, the largest ecological contribution with more than 99 %.

Table 2.6: LCA results of the CC impact category for all considered life cycle phases of one aircraft with a lifespan of 25 years.

Life Cycle Phase	**Global Warming Potential**		
	[$kgCO_2$-eq.]	[$kgCO_2$-eq./ASK]	[%]
Manufacturing	1,401,164	2.25×10^{-4}	0.19
Flight Operations	733,789,318	1.18×10^{-1}	99.70
Maintenance	789,165	1.27×10^{-4}	0.11
End-of-Life	-707,239	-1.13×10^{-4}	-0.10
Total	735,272,408	1.18×10^{-1}	-

Additionally, the impact categories Freshwater Eutrophication (FEP), ODP, and Minerals and Metals (MM) are exemplarily shown as pie charts in Figure 2.8, as the largest effects and variations (especially regarding the fuel production and combustion) can be seen here. However, the operational phase clearly represents the greatest impact in these

analyses as well. The results of all other impact categories for each life cycle phase can be found in the supplementary data.



(a) Freshwater Eutrophication (b) Ozone Depletion Potential (c) Minerals and Metals

Figure 2.8: LCA results for the FEP (a), ODP (b), and MM (c) impact categories.

2.5.2. Individual Results for the Life Cycle Phases

The following sections present the results for each life cycle phase individually. Each subsection concludes with a comparison to relevant literature values, though direct comparability is limited due to differing system boundaries and functional units across studies.

2.5.2.1. Manufacturing

According to the CC impact category, the production phase of an aircraft has a total impact of about 1,401 tCO_2-eq. calculated with the GWP. The largest share of this is related to raw material extraction (51 %) and processing and assembly (48 %). The transportation of the components to the FAL accounts for only 1 %. Based on the created inventory (Section 2.4.2), the corresponding environmental impact for each category can be analysed at the component-level, which is visualised in Figure 2.9. The power unit has the largest share in the majority of the impact categories. The selection of high-quality

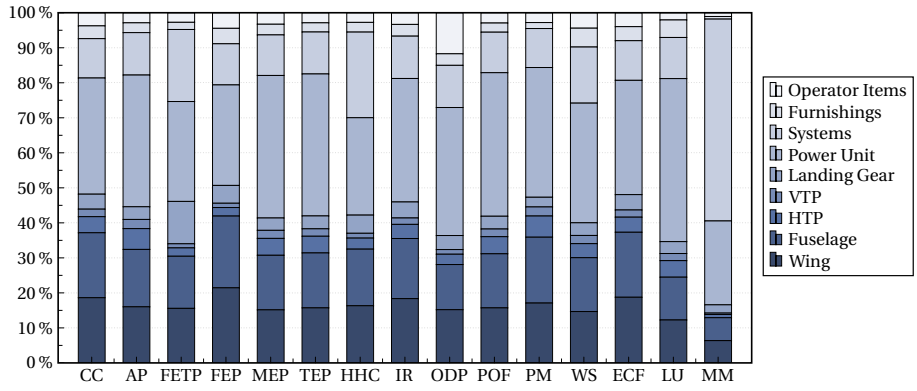


Figure 2.9: LCA results for the manufacturing phase across all impact categories.

and robust materials is a decisive factor in this context. In the CC impact category (first bar in the chart), its share is about 30 %, closely followed by the wings (19 %) and fuselage (18 %), whose ecological impact is mainly caused by their structural weight and material composition. The contribution of the different components is similar in almost all impact categories. An exception is the impact category of materials and metals, where systems have the largest share with almost 60 %. The reason for this high share is the considerable proportion of valuable metals, such as nickel, copper, and invar, which are particularly significant in the MM category. Pylons, landing gear, HTP, and VTP, as well as the operator items and furnishings have the lowest impact in most impact categories, mainly because of the relatively small mass of these components.

Comparison with Literature

For the aircraft manufacturing phase, the functional unit per OEW is most suitable for comparing the environmental impacts of the manufacturing phase with those from the literature. Figure 2.10 depicts the GWP of all considered studies in relation to the assumed OEW of the aircraft applied therein. A comparison is only applicable for GWP, as most studies only report their results in $kgCO_2$-eq. or use other LCIA methods, which makes a comparison for all of the impact categories used in this study impossible. The results of the LCA for the manufacturing phase differ significantly in the individual studies. The main reasons for these variations are different assumptions regarding the aircraft weight and its material composition. Nonetheless, the result of the present study falls within the average of all publications.

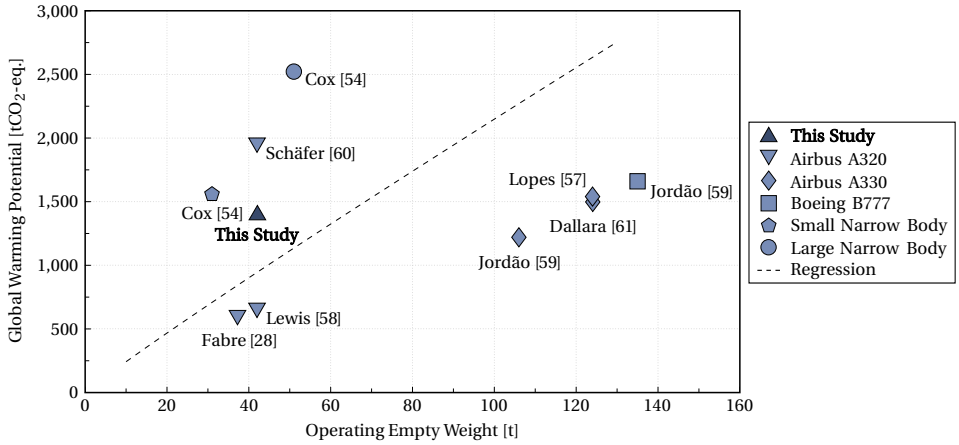


Figure 2.10: Overview of the GWP of this study and other publications over the associated OEW.

This is particularly visible when the values from the literature are normalised for direct comparison. A further comparison of the normalised ecological impacts in $kgCO_2$-eq. per kilogram of aircraft OEW is illustrated in Figure 2.11.

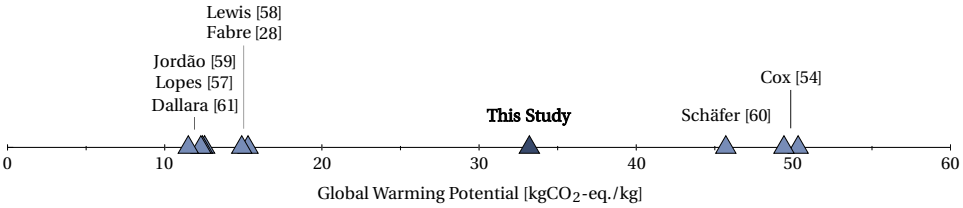


Figure 2.11: Comparison of the manufacturing impact of this study with outcomes from other publications (normalised by aircraft OEW).

2.5.2.2. Flight Operations

The ecological value of the flight phase depends primarily on the total lifetime of the aircraft and thus on the number of flights performed. This means that the longer an aircraft is in operation, the greater the ecological impact. Due to the different assumptions and boundary conditions in the published studies, the functional unit per ASK is used to compare the results. In this chapter, the calculated average value for an ASK based on a service life of 25 years and 150 PAX is 0.118 $kgCO_2$-eq. The total environmental impact of the operation is subsequently divided by the number of PAX and kilometres. Figure 2.12 illustrates the ratio of fuel production and combustion in all impact categories.

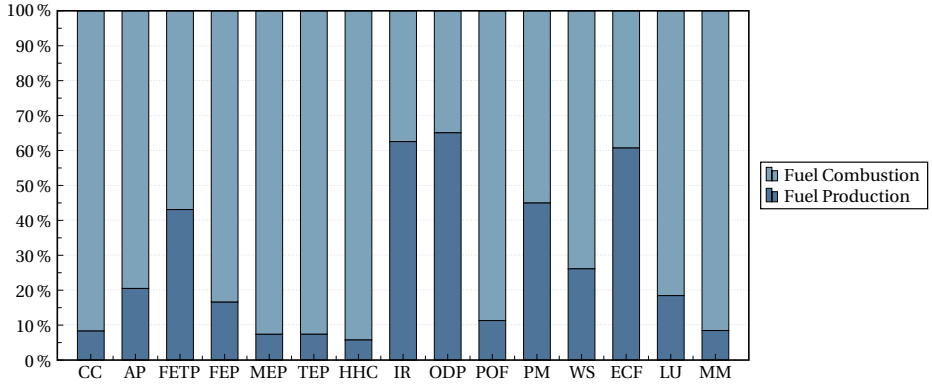


Figure 2.12: LCA results for the operation phase across all impact categories.

Fuel combustion has by far the highest share in almost all impact categories compared to the production of kerosene. In the CC category, for example, in-flight combustion causes an impact eleven times higher than the fuel production. This is primarily due to emitted GHG emissions, particulate matter, and NO_X, which are the main drivers in certain impact categories [115]. In other categories, such as Ionising Radiation (IR) and Energy Carriers (ECF), however, the share of fuel production exceeds that of its combustion for different reasons. Crude oil production contributes a share of more than 60 % to these impact categories. For the ODP impact category, instead, the high impact of kerosene production results, for example, from the chemical element halon 1301, as this is recorded in the ecoinvent database as an emission from petroleum production [116].

Comparison with Literature

Despite the complexity mentioned above, the operational phase is the most analysed life cycle phase in the literature. This is primarily due to the immense impact that it has on aviation. Most studies in this field only look at fuel-specific emission indices for CO_2, NO_X, hydrocarbons (HC), or carbon monoxide (CO) emissions, for which there are special engine emission databases [117] or calculate the environmental impact of the flight phase based on GWP or ATR. However, this approach does not represent an environmental LCA and should be treated with caution, which is why a comparison of the results is only possible to a limited extent. The unit CO_2-eq. per ASK serves as the basis for this analysis. The greatest similarities can be observed with the results of the studies by Chester [53] and Cox [54]. Figure 2.13 shows that the calculated environmental impact for the operation phase of this study (dark blue) aligns well with results from other publications.

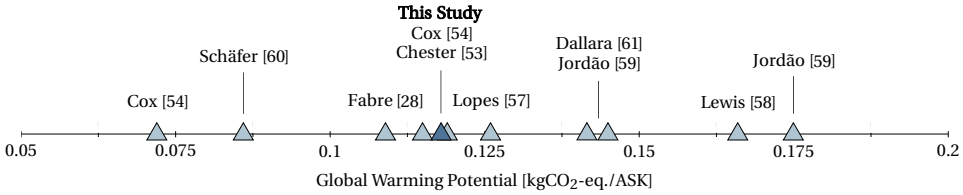


Figure 2.13: Comparison of the operations impact of this study with outcomes from other publications (normalised by ASK).

2.5.2.3. Maintenance

Similar to operations, the maintenance phase also depends on the lifetime and utilisation of the aircraft. The total environmental impact in the CC impact category for all maintenance activities is 1.27×10^{-4} $kgCO_2$-eq./ASK, whereby the largest share is caused by C-checks and shop visits (especially for the engine). C-checks occur rather rarely, but have a comparably high impact caused by their long maintenance durations. Moreover, these checks are carried out in the hangar, which represents an additional environmental impact because of the electricity consumption of the facility and equipment. The engine shop visit has a significant environmental impact due to its complex maintenance processes and the high number of spare parts that is needed for the overhaul.

An overview of all other impact categories is shown in Figure 2.14. Besides the CC, workshop visits have a very high impact in several other categories. For example, in the MM, the effect of component shop visits represents more than 65 % compared to all other maintenance checks. This is mainly due to the materials needed to manufacture the spare parts for the engine, landing gear, and APU. In the impact category ODP, daily and weekly checks in combination lead to a comparatively high environmental impact. One of the largest ozone-depleting substances is NO_X, which is produced, for example, by the operation of diesel-powered ground-based GSE, which are mainly used for ramp maintenance checks. The dominant contributors therefore differ substantially between impact categories.

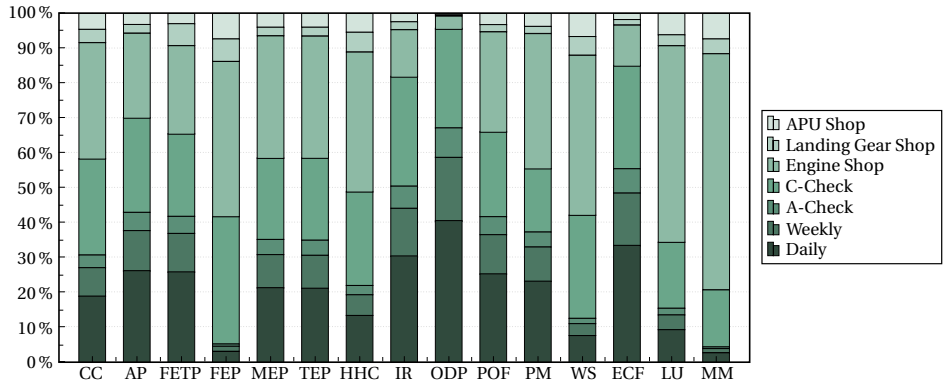


Figure 2.14: Ecological benefit due to the end-of-life phase (compared to the manufacturing phase) across all impact categories.

Comparison with Literature

Comparative values from the literature are rare. Many publications disregard the maintenance phase or integrate it into the operations phase in a simplified way. There are only very few values for the environmental impact of maintenance, which are all calculated on the basis of economic values. One of these is the consideration of the maintenance phase by Schäfer [60]. The author calculated the environmental impact (expressed in CO_2 emissions) based on the energy consumption of the maintenance processes and the resources needed for spare parts. The environmental impacts were calculated on the basis of direct maintenance costs for labour and materials and amount to 0.26 % of the overall life cycle (in comparison, this study has an ecological maintenance share of around 0.11 %). Chester [53] used various EIO-LCA sectors for manufacturing processes, including *aircraft engine and engine parts' manufacturing* for the environmental assessment of the maintenance phase, and obtained an overall value of about 2 % of the total life cycle. Another publication that examines maintenance independently is that by Jordão [59]. The author calculated the environmental impact of maintenance using the total energy consumption of the airport, the electricity price per kWh, and the maintenance costs based on aircraft block hours. The environmental share of maintenance is about 20 % of the total life cycle impact, which is significantly higher than other literature values due to the calculation using the economic approach.

2.5.2.4. End-of-Life

This study's end-of-life result is composed of the negative environmental impacts of aircraft dismantling and transportation to the end-of-life site, as well as the much higher positive environmental benefits driven by incineration, recycling, and re-utilisation. For analysing the end-of-life phase of the aircraft, the functional unit per OEW is applied again. Taking into account the end-of-life scenarios presented in Section 2.4.2.4, the environmental benefits from proper recycling and re-use amount to a total of -1.13×10^{-4} $kgCO_2$-eq./OEW, which corresponds to about 40.8 % of the environmental impact of the

manufacturing phase. In Figure 2.15, the positive environmental impacts in relation to the manufacturing of the aircraft are compared across all impact categories. The effect is particularly high for the impact categories of CC, FEP, IR, and ECF.

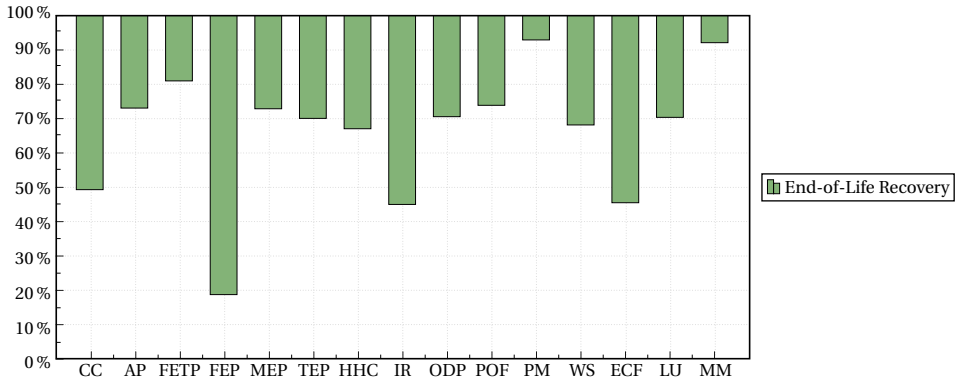


Figure 2.15: Ecological benefit due to the end-of-life phase (compared to the manufacturing phase) across all impact categories.

Comparison with Literature

Similar to maintenance, end-of-life is a phase that is often neglected in the literature. Only Schäfer [60] and Howe et al. [51] have considered an end-of-life scenario in their LCA studies. The environmental benefit calculated by Schäfer is based purely on CO_2 values and amounts to 5.7 % of that of the manufacturing phase. The author also conducted a parametric study with a 0 % and a 100 % recycling scenario (excluding CFRP) and obtained a negative impact of 1.1 % for the pessimistic and a benefit of 10.9 % in the optimistic scenario. In Howe's study, the total environmental savings based on GWP are 10 %. These are significantly lower than the values calculated here. One reason for this could be the rather optimistic view of the end-of-life scenarios with their relatively high recycling rates. As in the case of maintenance, there are large differences between these results and literature values caused by different assumptions and system boundaries.

2.5.3. Interpretation

In this study, the manufacturing, maintenance, and end-of-life phases are represented in considerable detail using a granular inventory, despite the numerous assumptions and estimations required due to limited data availability for the aircraft's mass and material breakdown. In addition, insufficient datasets in the ecoinvent database, especially regarding aviation materials or processes, led to further uncertainties. An expansion of the ecoinvent database or the creation of aviation-specific datasets is inevitable for future assessments in aviation. Further assumptions, such as the exclusion of the buy-to-fly ratio in material extraction, airport infrastructure, and non-scheduled tasks like brakes and tyres, could additionally be discussed in more detail in future studies. The comparison

with values from the literature showed that alternative solutions with EIO-LCA often deliver a significantly higher ecological outcome. This is due to the wider system boundaries typically adopted in economic analyses, which are based on entire industrial sectors.

In contrast, the environmental effects of the flight phase were determined using rather simple approaches, such as the ecoinvent database *market for kerosene* and *market for transport, passengers, aircraft*. Due to the combination of CO_2 and non-CO_2 effects, which have different impacts depending on geographic location and altitude, the pure consideration of emissions is not sufficient. Future propulsion technologies will further complicate the environmental assessment of flight operations by shifting impacts between flight and ground-based processes. However, even for current aviation systems, it is important to establish an aviation-specific LCIA methodology with different impact categories, as existing approaches do not adequately capture the specific characteristics of aviation emissions. Yet, the ecological assessment of flight emissions in the context of a holistic LCA is still fraught with many uncertainties. An uncertainty and sensitivity analysis was not performed in this LCA due to the complexity of this study. Possible uncertainty methods such as the Pedigree method [118] can, however, help to identify additional potentials for improvement.

2.5.4. Strengths and Weaknesses of a Discrete-Event Life Cycle Assessment Simulation

By combining LCA with discrete-event simulation, a more detailed analysis is possible compared to other rather streamlined LCA studies found in the literature. For example, it allows the ecological impacts to be calculated and analysed both based on individual event types and over the whole course of the life cycle. Figure 2.16 underlines that the temporal consideration of individual events during the operation time can have inherent advantages for the LCA values, which are otherwise calculated on the basis of average flight or maintenance hours per lifetime. The total environmental impact of flights (top) and maintenance events (bottom) is estimated based on the sum of the annual flight and maintenance events. Compared to the average value (black line), clear differences between the individual years can already be seen, as the flight and maintenance schedule result in individual variations in the operating phase. Especially when analysing the maintenance events, the effects become visible when major maintenance checks are carried out. Particularly in the years in which a longer C-check takes place (2025, 2031, 2037, and 2043), an increased ecological impact due to maintenance on the one hand, and a lower impact in the flight operations on the other, can be seen. This is due to the fact that the aircraft remains on the ground for the duration of the C-check. This effect is omitted in the case of the shop visits, as the aircraft usually receives an alternative component in order to continue flight operations during these checks.

Another advantage of discrete-event simulation is the possibility to analyse aircraft modifications and their effects on the remaining life cycle. Modifications can be manifold and are usually carried out to improve the aircraft efficiency. The impact on the environmental footprint is illustrated subsequently using an exemplary modification in the tenth year, leading to a hypothetical improvement in fuel efficiency of 10 %. Figure 2.17 shows the cumulative environmental impact of the unmodified aircraft (solid lines) compared to

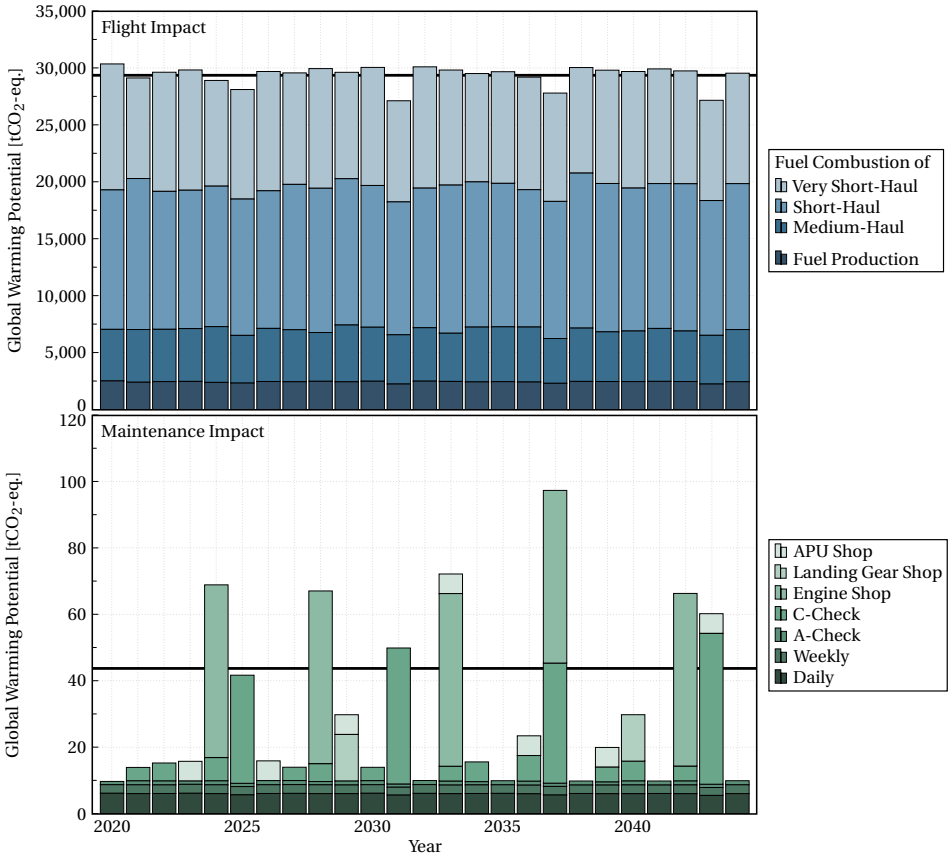
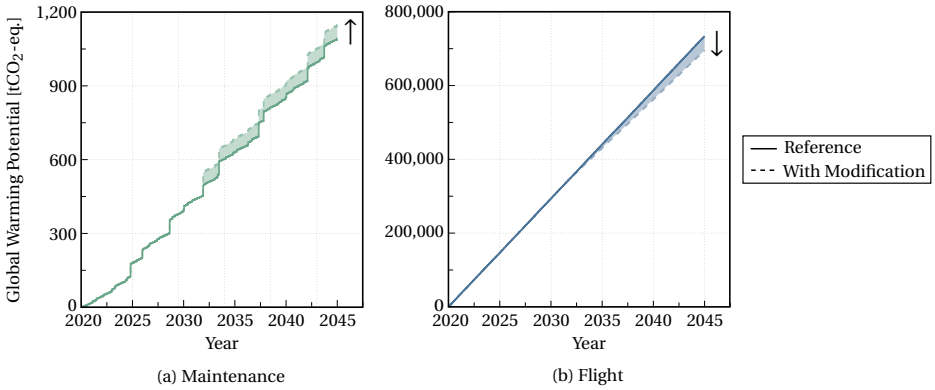


Figure 2.16: Effects of annually considered flight (top) and maintenance (bottom) events compared to usually on-average-determined ecological impacts (black line).

the modified one (dashed lines) for the flight and maintenance events. The modification event leads to an additional annual inspection event for the considered component. Although the environmental impact increases due to the additional maintenance tasks, this is outweighed by the savings resulting from the improved performance. At the end of the service life, this hypothetical modification can save almost 38,378 tCO_2-eq. and thus 5.2 % of the total impact over all life cycle phases. The applicability and advantages of a discrete-event simulation are thus multifaceted and offer a wide range of analysis possibilities compared to previous LCA studies in the field of aviation.

A summary of the advantages that the combination of discrete-event simulation and LCA offers compared to conventional ones is listed below:

- The ecological consideration of the discrete events allows a detailed analysis of the entire life cycle at both aircraft and event type level;
- Changes in the flight or maintenance plan can be made at any point in the life cycle, immediately reflecting the impact on subsequent operations;



(a) Maintenance (b) Flight

Figure 2.17: Cumulated changes in the environmental impact after a modification for maintenance (a) and flight (b) events.

- Integration of new aircraft technologies and associated maintenance tasks or modifications can be embedded into the life cycle without major effort;
- Each event provides temporal and geographical information for deeper analysis.

These advantages come at the cost of substantially higher data requirements and increased model complexity, highlighting the need for aviation-specific databases and comprehensive uncertainty analyses.

2.6. Summary and Outlook

This chapter presented an advanced combination of LCA and discrete-event simulation that is used to simulate and to environmentally assess the life cycle of an aircraft in detail. For this purpose, LCA was implemented in an existing life cycle simulation environment (LYFE) developed at the DLR Institute of Maintenance, Repair and Overhaul. Using the example of an aircraft similar to an Airbus A320 with an operating life of 25 years, each life cycle phase of the aircraft was thus evaluated individually on the basis of the existing parameters. Based on a detailed literature review and a selection of suitable comparative studies, it was further possible to validate the results of this LCA.

The findings of the extended LCA presented here fit well into existing publications and can serve as decision support for product development and operational planning. The study also showed the potential for further developments in the field of environmental assessment in aviation, for example, in the creation of an aircraft-specific database or LCIA methodology for more accurate assessment of the ecological impact of flight operations. In addition, an uncertainty analysis is essential to identify uncertainties. Within the DLR-internal project EXACT, the generic nature of this simulation is used to perform the evaluation of different aircraft types and the implementation of new aircraft technologies or modifications. Furthermore, it is planned to integrate time-dynamic aspects in subsequent studies in order to further strengthen the positive effects of the discrete-event simulation model and to enable a variety of additional analysis options.

Chapter 3

Beyond Flight Operations: Assessing the Environmental Impact of Aircraft Maintenance through Life Cycle Assessment

As the aviation industry strives to minimise its environmental footprint, understanding the full life cycle impacts, including maintenance, becomes essential for sustainable development. This paper addresses the critical research gap in the environmental assessment of aircraft maintenance by conducting a comprehensive life cycle assessment based on an Airbus A320 aircraft. By combining a top-down check-level analysis and a detailed examination of the aircraft manufacturer's maintenance planning document, this study provides significant insights into the environmental implications of maintenance activities. The check-level analysis provides a general overview, while the analysis of the maintenance planning document delves into individual tasks, enabling the identification of components with the highest ecological impacts. This research emphasises the importance of including aircraft maintenance activities in life cycle assessment studies and provides valuable guidance for researchers, industry practitioners, and policy makers in prioritising sustainability measures and enhancing the environmental performance of aircraft throughout their life cycle.

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3.1. Introduction

The aviation industry is under significant pressure to address and reduce the human-induced GHG emissions [33]. This requires a thorough analysis of environmental impacts to identify where, for example, the potential for climate change mitigation is particularly high. An LCA is thereby a commonly used method that comprehensively evaluates the environmental impact of an asset or process throughout its entire life cycle, including manufacturing, use phase, and end-of-life. Compared to other environmental assessment methods, LCA has the advantage of not focusing on just one environmental impact, such as the carbon or water footprint. Instead, it looks at different aspects, avoiding potential burden-shifting in environmental impact and providing a more comprehensive picture of the overall environmental impact [119].

While many LCA studies in aviation focus on the environmental impacts of flight operations, the ecological aspects of aircraft maintenance have not been sufficiently examined. This may be attributed to the perceived low environmental impact of maintenance in the aircraft life cycle, which does not seem to justify the considerable effort required for data collection and modelling [37]. However, aircraft maintenance is a highly complex discipline, with a variety of different types and categories of maintenance tasks performed at specific intervals. For instance, a conventional aircraft undergoes more than 2,000 different maintenance events per year[3] most of which are differentiated by their activities. Without these essential maintenance events, the highly coordinated air travel would not be possible today, as ensuring the airworthiness of aircraft is paramount for their safe operation, contributing to their prolonged service life and sustained efficiency. According to a report by Airbus [120], Maintenance, Repair, and Overhaul (MRO) activities were considered to be of significant importance for both short and long life cycles. This relevance also stems from the direct impact on the product during its in-service life, despite its associated environmental impact. These contrasting positions complicate the understanding of the true ecological impact of aircraft maintenance and the identification of critical factors.

This chapter aims to address the research gap in the environmental assessment of scheduled maintenance activities using the case study of an Airbus A320 aircraft. To address the complexity of aircraft maintenance and achieve a comprehensive assessment of MRO in general, a combination of two approaches is used. A so-called check-level approach provides a top-down overview of the entire maintenance process that can be contextualised within the overall life cycle of the aircraft. The checks represent aggregated maintenance packages that do not list detailed tasks but provide general insights into an entire set of MRO activities. In addition, an in-depth analysis is employed in order to gain a more thorough understanding of individual tasks using the aircraft manufacturer's Maintenance Planning Document (MPD). This approach provides very detailed information on specific tasks and therefore gives a more thorough perspective on the environmental impact. The study aims to gain a comprehensive understanding of the associated impacts of aircraft maintenance as a basis for evaluating and developing both sustainable maintenance technologies and strategies. Moreover, the developed approach

[3]The annual average number of maintenance events was calculated based on Aircraft Commerce [88], with an average utilisation of 2,500 FHs per year and a FH/FC ratio of 1.5 of an Airbus A320.

enables the environmental maintenance assessment of novel aircraft technologies at a detailed level - even if they are still in the conceptual phase.

The chapter is structured as follows: First, an overview of maintenance activities and current approaches for environmental assessment is given as a foundation for the combined LCA methodology that is described subsequently. After that, we describe the generation of the LCI and analyse the LCIA results regarding the main drivers of the ecological implications to identify the possible reduction potentials. A sensitivity analysis then shows the influence of operational factors, such as the aircraft usage profile, on the environmental impact. Therefore, two different flight schedules, with short- and long-haul flights, and contrasting airline business models with different maintenance management practices are compared. The final conclusion and outlook summarise the results and provide information on how this approach can contribute other LCA practitioners when evaluating, for example, new aircraft technologies in the future.

3.2. Fundamentals

This section introduces the fundamentals of aircraft maintenance that are relevant for this study. Building on these technical aspects, the current state of research on LCA studies of aircraft maintenance is reviewed.

3.2.1. Aircraft Maintenance

MRO is an essential process that includes technical, administrative, and management measures throughout the lifespan of an aircraft, with the aim of restoring or maintaining it in a functional state to achieve its required function [121]. The aviation industry places great emphasis on maintenance as it ensures the continued airworthiness of the aircraft and restores the level of safety and reliability established during design and manufacture.

A distinction is drawn between routine and unscheduled maintenance. Unscheduled maintenance is a procedure that is not part of the regular planning process and is primarily performed in response to detected system abnormalities due to the unpredictability of certain technical wear processes. An unplanned maintenance activity can be triggered either by condition-based monitoring or by damage-related events that require immediate attention and repair [122]. Scheduled maintenance, on the other hand, involves pre-planned inspections and servicing of aircraft components at specific intervals to ensure continued airworthiness. In aviation, the maintenance strategy plays a crucial role in determining the timing and scope of required maintenance activities. The following parameters, either individually or in combination, can determine the maintenance interval according to the “whatever occurs first” principle [104]:

- The time a component has already been in operation (in days, months, or years);
- The number of FHs;
- The performed FCs, whereby a cycle begins with the take-off of the aircraft and ends after landing;
- The aircraft’s operational environment (influenced by factors such as high or low outside temperatures, humidity levels, and the amount of dust and salt in the air).

They help to detect and prevent fatigue, environmental wear, and degradation. Especially for scheduled maintenance, it is crucial to classify aircraft components according to one or more of these threshold parameters and to ensure that they are replaced or repaired before their limit is reached. However, once established, these intervals can be adjusted as operational experience is gained and the maintenance philosophy evolves [123]. Such adaptations can have lasting effects on the maintenance estimation of technologies that are either yet to be introduced or for which there is limited practical experience [12].

3.2.1.1. Line, Base, and Shop Maintenance

Commercial aircraft maintenance classically encompasses line, base, and shop maintenance [104]. Line maintenance involves regular tasks, such as visual inspections or minor repairs, to ensure aircraft airworthiness, performed on a daily or weekly basis at either an operator's home base or at outstations. The line maintenance contractor works closely with flight crews to resolve reported issues and to ensure the aircraft is in optimum condition for the next flight, with a focus on rapid turnaround times to meet scheduled departures. In contrast, base maintenance occurs less frequently, typically every few months or years, and involves comprehensive inspections and repairs that require the aircraft to be temporarily taken out of service. Base maintenance usually takes place in hangars, providing a controlled environment, good lighting conditions, and special equipment [105]. The frequency and extent of shop maintenance operations, on the other hand, are closely linked to safety-critical components with defined lifetime constraints, known as Life Limited Parts (LLPs) [124, 125], being for example part of the jet engines or landing gears. The overhaul of these components is carried out in specialised facilities with certified technicians, while the aircraft often receives a replacement component for continuing its service during this time.

3.2.1.2. Maintenance Checks

The execution of maintenance activities follows pre-defined intervals that serve as a guideline for the bundling of individual maintenance activities. These maintenance packages can be divided into different levels or letter[4] checks (e.g., A, B, C), with each letter defining a specific scope of maintenance activities [126]. A- and B-checks are part of line maintenance, usually shorter, and performed on a regular basis, while the C- and D-checks are more complex and performed less frequently. They are considered as part of base maintenance. The scope and frequency of these checks may vary based on aircraft type, manufacturer specifications, and regulatory requirements. In addition, aircraft maintenance includes a number of non-letter checks, such as pre-flight, transit, daily, and weekly checks, which contribute significantly to the overall airworthiness and operational readiness of the aircraft, especially within shorter time horizons. All checks are interrelated; e.g., the weekly check includes daily check tasks, thus eliminating the need for a daily check on a day when a weekly check has already been performed [88, 104, 127].

[4] It should be noted that the labels of the checks can vary, but many maintenance organisations and airlines use the letter checks mentioned above. The B-check is no longer used for most commercial aircraft, due to changes in maintenance practices and advances in aircraft technology [105, 126].

3.2.1.3. Maintenance Planning Document

The MPD contains the aircraft manufacturer's recommended maintenance program, providing essential planning information to individual aircraft operators for specifying their own maintenance schedules. In addition, the MPD provides detailed information on the execution of recurring maintenance tasks. This includes, for example, the exact description of the tasks, information on the average time required for execution (excluding time requirements for materials, resources, and document procurement), references to technical publications, access instructions, and the equipment to be used. In addition, each task is assigned a dedicated task code, which main description can be found in the MPD itself [128].

3.2.2. Life Cycle Assessment of Aircraft Maintenance

In the field of environmental impact research in aviation, considerable attention has been given to conducting comprehensive LCAs of specific aircraft types or making comparisons between different aircraft configurations, modes of transport, and materials. The aspect of aircraft maintenance has typically been considered within the broader context of flight operations and assessed using various LCA methodologies, although in most cases in a simplified manner.

Several researchers [52, 53, 129, 130] have used the EIO-LCA method to investigate the environmental impact of an aircraft's life cycle including maintenance activities. This method establishes a link between the economic performance of a specific industry and its corresponding environmental metrics. However, there are inherent uncertainties due to the lack of a dedicated aircraft maintenance sector within the EIO-LCA methodology [53]. In the analysed studies, maintenance is approached in different ways. Aihara et al. [130] combined maintenance with vehicle production, resulting in only a 1 % contribution to CO_2 emissions in passenger transport. In the study by Facanha & Horvath [52], the aircraft's end-of-life was additionally merged with maintenance activities and accounts for a total life cycle share of around 20 %. Only Chester & Horvath [129] presented separately assessed results showing that MRO activities account for approximately 2 % of the total life cycle environmental impact when using the EIO-LCA method.

Other studies have used specialised LCA databases, such as the ecoinvent database [29, 57, 58, 63, 131]. These databases, though, solely offer data on airport maintenance and not specifically on aircraft maintenance, making them unsuitable as a basis for comparison in this study. Schäfer [60] calculated the environmental impact of maintenance based on the energy consumption of individual processes and spare parts. The results of this streamlined LCA were only presented in terms of CO_2 emissions and represent merely 0.26 % of the overall life cycle impacts. Other studies have examined the energy consumption of airports [35, 42, 59, 132]. Yet, without the ability to differentiate the consumed resources due to maintenance versus other airport or logistic operations, it is difficult to accurately calculate the environmental impact of maintenance with its wide range of tasks that can vary according to aircraft type, age, operating conditions, and other factors. Jordão [59] further post-processed his findings by incorporating the calculated electricity consumptions with maintenance costs based on aircraft block hours. This approach results in an environmental share of 20 % of the total life cycle, which is relatively high compared to

other studies in the literature, but consistent with the share of direct maintenance costs in the total aircraft service life. Yet, the feasibility of a direct translation from costs to ecological factors remains a subject of debate [133].

Alternative approaches such as weight calculations [134], exergy analysis [40], or consideration of carbon pricing [135] have been employed to assess maintenance impacts. However, none of these methods allows a detailed examination of specific maintenance aspects. Due to the lack of specific data on aircraft maintenance activities [18], it is not possible to assess the environmental impact on, for example, the component-level. As a result, some comparative studies have intentionally excluded the analysis of the environmental impact of maintenance activities [28, 47, 48, 136]. These studies assume that there is little variation in maintenance activities between aircraft types or due to different materials and configurations. Krieg et al. [37], for example, argues that the relatively small environmental impact of maintenance does not justify the considerable effort required to collect and model the data. Conversely, a recent study by Barke et al. [31] emphasised the critical role of maintenance, in particular the replacement of components, in environmental considerations during the use phase of the aircraft. The authors also highlighted the potential increase in maintenance effort, especially for emerging propulsion concepts, due to the shorter lifetimes of new technologies. In the study, especially batteries and fuel cells have a particularly large impact due to component replacements in the impact categories CC, mineral resource depletion, and fossil resource depletion. The application of novel technologies and processes in maintenance activities, such as additive manufacturing for spare parts or repair technologies, should be further explored in terms of energy, material, and water requirements [137, 138]. In order to gain a better understanding of the impact of new technologies on the environment, maintenance must be given a more significant role [139].

This literature overview highlights the existing challenges and uncertainties associated with accurately capturing and analysing the specific environmental impacts of maintenance activities. While previous research has used a variety of methods and approaches to assess these impacts, a detailed and comprehensive approach that allows a granular analysis of MRO activities is currently lacking. Furthermore, it is often very difficult to compare results from the existing literature, as aviation maintenance is often not considered as a whole or is examined in varying levels of detail due to different boundary conditions and data availability.

3.3. Method

In the following section, an LCA approach, as defined by ISO 14040/44 standards [21, 22], is presented to investigate the environmental impacts of aircraft maintenance activities. Along with a description of the methodology, the goal and scope, including the system boundaries and functional units, are described. In addition, we provide a more detailed description of how the LCI is generated, both based on the maintenance checks and from the MPD.

3.3.1. Combined Top-Down and In-Depth Analysis

The methodology of this study is designed on the basis of two data sources. Firstly, a check-level approach is used to examine the overall maintenance processes. In this approach, maintenance activities are initially categorised into line, base, and shop maintenance, and then further aggregated. Line and base maintenance are then subdivided into checks, while shop maintenance focuses on the maintenance of large components. Secondly, to complement the top-down approach and provide a more in-depth analysis of single tasks, a detailed examination of the MPD is conducted. In addition, the MPD can be used to assign specific tasks to so-called Air Transport Association (ATA) chapters. The ATA chapter system serves the unification and standardisation of aviation documents and subdivides groups and subgroups of aircraft components.

This integrated approach provides a more robust and comprehensive understanding of the ecological implications of aircraft MRO than previous studies. A schematic representation of this methodology is provided in Figure 3.1. Pre-flight and transit checks routinely involve only visual checks by the pilot or flight crew and are therefore excluded from the analysis as they have no direct environmental impact. The MPD only includes tasks that are part of line and base maintenance (daily to D-check). Shop maintenance activities are also not included in the MPD.

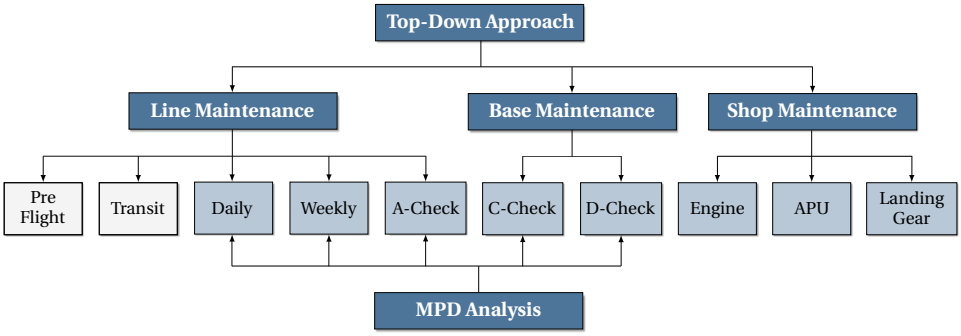


Figure 3.1: Overview of the combined methodology for the assessment of aircraft maintenance.

3.3.2. Goal and Scope Definition

The goal and scope phase is an important step in the LCA, in which the purpose and the methodology of the study are defined. It sets the goals of the assessment and defines the system boundaries to focus on the relevant environmental impacts and activities.

3.3.2.1. Use Case

The Airbus A320 was chosen as a use case due to the large data availability and the broad knowledge and experience in the industry resulting from its many years of operation. The DLR-internal discrete-event simulation framework named LYFE, which simulates the life cycle of an aircraft based on flight schedules and maintenance intervals, was used as a

foundation to calculate the frequency of individual maintenance tasks over the whole lifetime of one aircraft. In addition, economic and environmental assessments can be applied to provide insight into operational and design trade-offs. In this study, an aircraft's service life of 25 years based on the International Civil Aviation Organization (ICAO) [140] was assumed. A detailed description of how LYFE works can be found in Rahn et al. [141] and Pohya et al. [85]. In the present study, flight schedules from Burschyk et al. [142] were used to represent different operational scenarios. These consisted of schedules for different airline business models (so-called Full-Service Network Carriers (FSNCs) and Low Cost Carriers (LCCs)[5]), each with a short-haul and a long-haul schedule. The baseline for this study was the FSNC schedule with mainly short-haul flights and an annual average of 2,200 FH and 1,930 FC, which also reflects the average usage profile of an Airbus A320 [123].

The maintenance intervals and downtimes used in this analysis are shown in Table 3.1 and are based on multiple sources [88, 104, 143–145]. For simplification, the FHs for the components, such as the jet engine or the APU, were set equal to those of the aircraft. Apart from the engine shop visit, engine maintenance also included the replacement of certain LLPs, which have their own maintenance intervals. These LLPs are single components, such as discs or shafts, which in turn are parts of component modules. For simplicity, only the modules and their respective lifetimes were considered here, which consisted of the fan (30,000 FC), the compressor (20,000 FC), the high-pressure turbine (20,000 FC), and the low-pressure turbine (25,000 FC) [88, 124]. For simulation purposes, the exchange of LLPs was included in the closest shop visit.

Table 3.1: Initial input for every maintenance check including durations and intervals (merged from [88, 104, 143–145]).

Check	**Duration**	**Interval**
Daily	2 h	1 day
Weekly	3 h	7 days
A-Check	10 h	450 FH
C-Check	168 h	5,000 FH
D-Check	672 h	6 years
Engine Shop	672 h	9,000 FH
APU Shop	336 h	7,000 FH
Landing Gear Shop	1,009 h	10 years

The study primarily examined preventive, planned, and routine maintenance activities. This was chosen due to the high unpredictability and variability associated with unplanned and non-routine maintenance, which could significantly increase uncertainties. The LCA was conducted using the ecoinvent version 3.9.1 database, adhering to the allocation, cut-off by classification system model [146] and the EF 3.0 LCIA methodology [147].

[5] An FSNC is an operator that offers a comprehensive range of services, including multiple destinations, different cabin classes, and additional amenities to meet the needs of leisure and business travellers. LCCs differ from FSNCs in that they typically operate with shorter turnaround times and therefore offer more flights per day.

Figure 3.2 illustrates a process flow diagram of the LCA approach. After defining the system boundaries, input data was collected from various sources, such as the ecoinvent database, scientific literature, and expert opinions, to form the basis of the LCI. The LYFE tool was then applied for the life cycle simulation. Therefore, specific input data was required, including maintenance and flight schedules, as well as additional aircraft-related information. This step was critical for a full understanding of all maintenance activities and their occurrence over the aircraft's lifetime. Following, the execution of the LCIA with the open-source python-based framework Brightway2 [148] was performed to evaluate the environmental impact of these maintenance events. The final step was to interpret the results in order to assess the overall environmental impact of aircraft maintenance and identify areas for improvement. Additionally, the four standardised steps of the LCA are depicted on the right side of the figure.

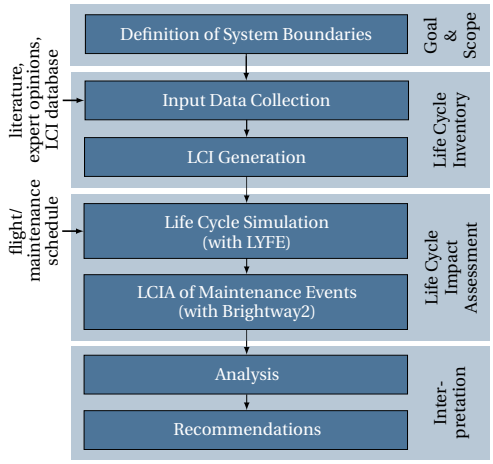


Figure 3.2: Process flow of the LCA approach.

3.3.2.2. System Boundaries

The maintenance activities were mainly carried out in Germany, or where no further data available, in Europe.[6] The consideration of the location was critical in determining transport routes and logistical factors. The assessment excluded the end-of-life phase, and, therefore, waste treatment and recycling, due to the high complexity of this phase and the already very data-intensive inventory phase. Similarly, products and processes that have a secondary role in their use were not considered. For instance, the production of lamps, when assessing the energy consumption, or rags used for cleaning were not taken into account. Additionally, the manufacturing and maintenance of tools and equipment, as well as the transportation of products within the maintenance site, were excluded from the analysis. Moreover, impacts related to the maintenance staff, such as personal

[6] An overview of the used datasets and selected locations can be found in the supplementary information.

waste or commuting to the site, were not considered. These interrelations are illustrated in Figure 3.3.

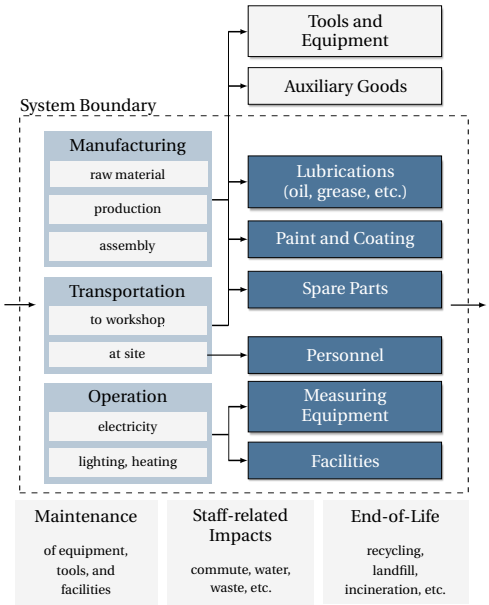


Figure 3.3: Overview of the system boundaries of the presented study.

The assessment results are presented in both absolute terms and normalised according to the functional units per FH and per ASK. This approach facilitates comparisons of LCA outcomes across various operational scenarios.

3.3.3. Generation of the Inventory

A preliminary analysis was required to create the inventory. The starting point was the analysis of the individual checks, which provided an overall view of the ecological implications of scheduled maintenance activities in general. The MPD analysis was then used to assess individual tasks in detail, but did not cover certain aspects such as the energy consumption of the hangar and equipment. This was supplemented by the results of the check analysis to provide a complete inventory. The generated LCI was compiled from a variety of literature sources, including brochures, training materials, and expert interviews. Due to the large number of references and to keep the chapter concise, not all referenced sources are listed in this article. Instead, all sources, along with additional details are provided in the supplementary material to this article.

The collected foreground data is linked with background data from the ecoinvent database. The ecoinvent database serves as a comprehensive collection of LCI data commonly utilised in LCAs and environmental evaluations; however, it is not specialised for aircraft-specific applications or materials. For instance, specialised aviation alloys, which also hold significance in MRO activities, are currently not covered in the database.

To improve the quality of the background data in this study and illustratively enhance the methodology, an adapted dataset was employed for the titanium alloy Ti64, which is one of the most commonly used materials in the spare parts of engines, landing gears and APUs. The composition of the Ti64 alloy, along with the manufacturing energy consumption of approximately 60 kWh per kilogram of a produced titanium component, is derived from Denkena et al. [94] and the U.S. Department of Energy [95].

3.3.3.1. Inventory from Maintenance Checks

For the check-level approach, it was important to consider the main activities of each check in more detail. Pre-flight and transit checks performed at the gate involve only visual inspections and the correction of out-of-scope repairs, which have no apparent environmental impact [88]. The daily check, on the other hand, includes visual inspections and engine oil servicing, which require the use of GSE, such as a GPU and the transport of specialised personnel to the aircraft's location on the apron. Weekly and A-checks also include visual inspections and are typically carried out in a hangar, where the main contributor to their environmental impact is the operation of the facility. Base maintenance, which includes both C- and D-checks, is much more work-intensive than line maintenance inspections and requires the use of GSE and electricity for the Heating, Ventilation, and Air Conditioning (HVAC) of the hangar. Beyond that, special equipment is used and parts of the aircraft are dismantled for inspection. In the case of workshop visits, certain components are first taken to a repair shop where they are cleaned and overhauled. An average transport distance of 500 km was assumed based on German maintenance locations and their average distances to the largest international German airports [149]. Cleaning and replacement of parts with a limited service life were calculated on the basis of the component dimensions. In addition, workshop activities such as lighting or special equipment were also taken into account.

This approach is illustrated by the example of the A-check, which was carried out on average every 450 FH [88] and took about ten hours. According to Hinsch [104] and Augustine et al. [150], the standard A-check includes typical tasks such as changing filters, checking and lubricating important systems (hydraulics of control surfaces, landing gears, etc.), and checking emergency equipment. The quantity of replaced filters, consisting of synthetic material fibres, was estimated at an average of 1 kg with the help of expert interviews and engineering guesses, while the oil change was calculated at 3.15 kg per check [151]. We assumed that the A-checks took place in the hangar, meaning the aircraft had to be towed into the hangar with the help of a towing vehicle. The energy consumption of the facility was calculated based on aircraft size and its proportional use. Energy consumption values for the hangar were determined from literature data [152], giving annual values of 280,000 kWh for lighting and 246 kWh/m^2 per year for HVAC, scaled to the aircraft area (2,500 m^2 for an Airbus A320 [107]). An additional GPU supplies the aircraft with electrical energy when the engines are not running to operate the electrical systems on board, such as lighting, air conditioning, avionics, and other electrical equipment. Due to data availability, this study assumed that the GPU was diesel-powered [153]. With this approach, an initial inventory could be generated for all recurring maintenance checks, which was mainly limited to routine tasks such as oil changes and energy consumption

of equipment and facilities. The full overview of all maintenance tasks with a list of used references can be found in the supplementary material. Information on maintenance tasks at the component-level was then supplemented with the help of data from the MPD.

3.3.3.2. Inventory from Maintenance Planning Document

In addition to the check-level LCI, the MPD was used to identify detailed maintenance actions. The MPD included checks with a minimum interval of three days, covering tasks from daily up to D-check. As the Airbus A320 MPD applies to all aircraft of the Airbus A320 family (e.g., A319, A321, or A320neo), it was first necessary to filter out all tasks related to the Airbus A320ceo with the CFM56-5 engine and modified wing that was considered in this study. The so-called *Applicability* could be used to specify further aircraft specifications that needed to be defined to avoid duplication of tasks, resulting in a total number of 1762 relevant tasks. Each task in the MPD was marked with a so-called task code, which provided sufficient information about the type of maintenance activity and could thus be used to bundle tasks. Further information on task codes could be obtained from the MPD [128]. Table 3.2 provides an overview of all task codes, their description, and the type of the derived environmental impact.

Table 3.2: Overview of all MPD task codes and activities [128].

Task Code	**Name**	**Activity** (other than hangar and equipment)
CHK	Check	-
DET	Detailed Inspection	-
DIS	Discard	replacement of components
FNC	Functional Check	transportation to workshop
GVI	General Visual Inspection	-
LUB	Lubrication	application of lubricants
OPC	Operational Check	transportation to workshop
RST	Removal/Restoration	cleaning of components transportation to workshop
SDI	Special Detailed Inspection	use of special measurement equipment transportation to workshop
SVC	Drain, Servicing, Replenishment	exchange of fluids draining of components
VCK	Visual Check	-

For the tasks with the codes *CHK*, *DET*, *GVI*, and *VCK*, the energy consumption of the facilities was found to be the main influencing factor since these tasks only require personnel and mechanical equipment. Repair task codes, such as *OPC*, *FNC*, *SDI*, and *RST*, were analysed individually, taking into account the mass and number of components, the transport distances to workshops, and the number of tasks per life cycle. Additionally, the *RST* tasks revealed a significant impact on cleaning tasks, with 91 % of the measures being related to cleaning with compressed air and a water-alcohol mix [154]. For the *SDI* tasks, the use of specialised measurement equipment, such as endoscopes, borescopes,

and other battery-operated devices, was identified as the main source of environmental impact [155]. The *LUB* and *SVC* tasks involve the exchange of lubricants and fluids, and for the *DIS* tasks, the mass, material, and number of components to be replaced were determined. Expert knowledge was required to determine the type, density, and amount of lubricants and fluids used in the *LUB* and *SVC* tasks. The bar chart in Figure 3.4 gives an overview of the proportion of task codes in the MPD.

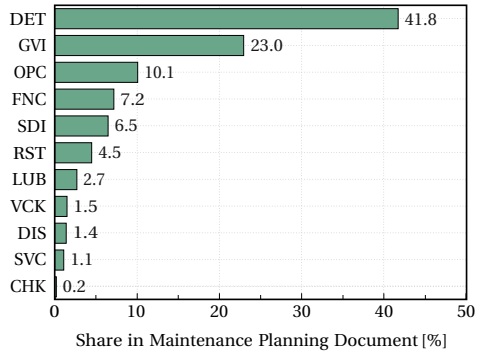


Figure 3.4: Share of task codes in the number of maintenance tasks in the MPD.

An example is given with task number 212141-01-1, which describes the replacement of filter elements that are part of the air conditioning recirculation system (ATA 21). The material of the filter element is polyester [156] and a mass of 3 kg [157] could be determined from the literature, which was then used to calculate the environmental impact of this discard task using the ecoinvent database.

To calculate the total number of task executions over the life cycle of the aircraft, the lowest threshold or interval (in calendar time, FH, or FC) that applied in this study was first determined. The men hours and the number of mechanics could be combined to determine the duration of the task. Yet, the impact of the equipment or operation could not be considered at this stage as it was not possible to distinguish how many MPD tasks are performed in parallel. To take this into account, the number of men hours was presented as a percentage of the total maintenance time and compared with the equipment and hangar operating values from the check-level assessment. For the subsequent calculation, a factor of three has been used for the realistic number of men hours, based on expert opinions and information from Aircraft Commerce [88]. The results of this detailed approach could then be evaluated holistically at the ATA chapter-level.

3.4. Results

This section first presents the LCI, which has been compiled from the maintenance documents and can be fully accessed in the supplementary material. The results of the LCIA calculations are then presented in Section 3.4.2 for CC and a selection of other impact categories. Finally, Section 3.4.3 provides a sensitivity analysis and shows the relative importance of maintenance activities in relation to the operational profile.

3.4.1. Life Cycle Inventory

The inventory consists of both the maintenance checks and the individual tasks in the MPD. Table 3.3 shows an example of the A-check (described in Section 3.3.3), including the relevant standard activities of this check and excluding some routine activities, such as visual tasks that are performed by the flight crew without equipment.

Table 3.3: Extract from the inventory covering the activities related to the A-check.

Activity	Influencing Factor	Quantity per Check
discard of filters	synthetic material fibres	1 kg
engine oil servicing	engine oil	3.15 kg
ground power unit	diesel	30 l/h
aircraft towing	electricity	10 kW
hangar operations	electricity	76.7 kWh

In addition, there were a number of activities that are not a direct requirement of the aircraft manufacturer but are nevertheless regularly performed by operators or MRO providers. Aircraft repainting and cabin refurbishment are typically carried out every six to eight years, which corresponds to the D-check interval. A regular engine wash is performed about every three months [109] and a tyre replacement is conditionally carried out approximately every 250 FC for the nose wheel and every 350 FC for the main wheel [158]. For the sake of simplicity and because the study did not distinguish between nose and main landing gears, tyre replacements as well as engine washes were integrated into the A-check. The full LCI is provided in the supplementary material.

Furthermore, the tasks listed in the MPD were thoroughly processed and categorised on the basis of their respective task codes. A selection of these datasets, including references, is provided in the supplementary material. These datasets comprises the full LCI data for all maintenance checks, together with a comprehensive analysis of the inventory for MPD tasks. As a representative example, we have only included tasks related to the air conditioning system (ATA 21), due to the extensive nature of the MPD and the fact that it is not publicly available. Whenever references are made to energy consumption associated with the hangar and equipment, the data is derived from the MPD's men hours and the top-down approach.

3.4.2. Life Cycle Impact Assessment Results

The results of the study provide a detailed analysis of the environmental impacts of aircraft maintenance activities at the check- and component-levels. This research highlights the specific areas where environmental improvements can be targeted. The following section presents the key findings derived from the LCA.

3.4.2.1. Global Warming Potential

The initial results focus on the impact category of CC and the associated GWP, expressed in kilograms of carbon dioxide equivalents ($kgCO_2$-eq.), which is the most commonly

used indicator as it allows the aggregation of GHG emissions from different origins. A selection of other impact categories of the LCIA EF 3.0 methodology and their results are also highlighted. An overview of all results can be found in the supplementary data.

Results for Maintenance Checks

An overview of all checks over the whole life cycle is shown in Figure 3.5. After simulating the aircraft's operational life cycle with LYFE, the total environmental impact of maintenance events was aggregated for each year and plotted in the bar chart. There were significant differences between the years, particularly in connection with base maintenance and workshop visits. The greatest environmental effects occurred in the years 6, 12, 18, and 24, when the major D-check took place and the cabin was replaced. The sum of line maintenance checks remained almost constant each year throughout the aircraft's life. Minor annual variations occur because daily checks are included in higher-level maintenance checks (e.g., weekly or A-checks) and are therefore omitted whenever these checks are performed. The daily check had the highest environmental impact among all checks, with more than 543.4 tCO_2-eq., accounting for 34.9 % of the total impact. This was followed by the D-check, which included hangar operations, cabin refurbishment, aircraft repainting, and other activities, and resulted in a total impact of over 20.2 %, causing a total environmental impact of 313.7 tCO_2-eq. The C-check had the lowest overall environmental impact of all the checks with only 5.0 % and about 77.8 tCO_2-eq.

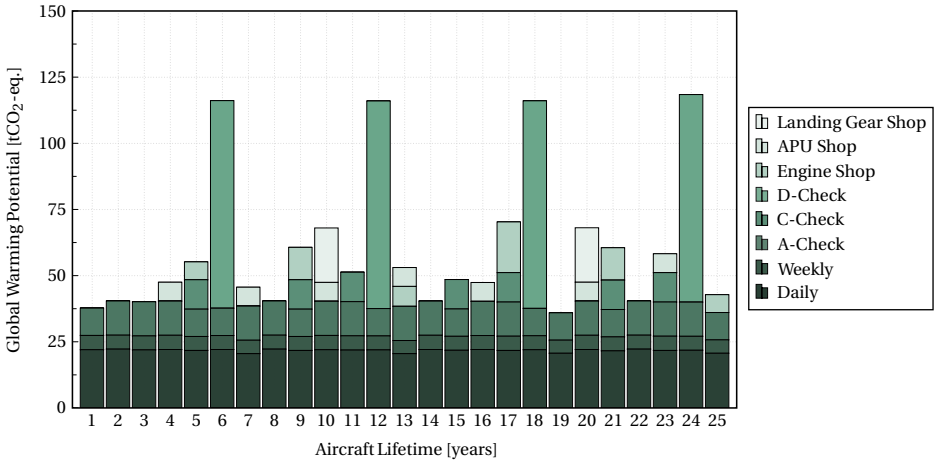


Figure 3.5: Distribution of maintenance-related environmental impact over the whole life cycle of the aircraft.

An overview per maintenance type can be seen in Table 3.4. Line maintenance accounted for about 64.1 % in total, followed by base maintenance with 25.2 %. Workshop visits accounted for a relatively small share of maintenance with only about 10.7 % and a total of 167.2 tCO_2-eq. Looking at the environmental impact per flown hour, this ranged between 3.0 $kgCO_2$-eq./FH (for shop maintenance) and 18.1 $kgCO_2$-eq./FH (for line maintenance).

Table 3.4: Overview of the environmental impact of maintenance types in terms of their GWP in relative, absolute, and normalised (in FH) values.

Maintenance Type	Global Warming Potential		
	[%]	[tCO_2-eq.]	[$kgCO_2$-eq./FH]
Line Maintenance	64.1	996.1	18.1
Base Maintenance	25.2	391.5	7.1
Shop Maintenance	10.7	167.2	3.0

Results for Component Groups

The MPD uses the ATA chapter assignment to facilitate the systematic categorisation of maintenance tasks into specific component groups. Tasks that cannot be assigned to a single chapter are referred to as zonal tasks. Engine wash, tyre replacement, cabin refurbishment, and shop activities were allocated to the corresponding ATA chapters as appropriate. Aircraft repainting was excluded from the categorisation due to its association with several component groups. Figure 3.6 provides a visual representation of the distribution of environmental impacts across all ATA chapters. However, not all ATA chapters are included in the MPD, as some component groups cannot be assigned maintenance tasks.

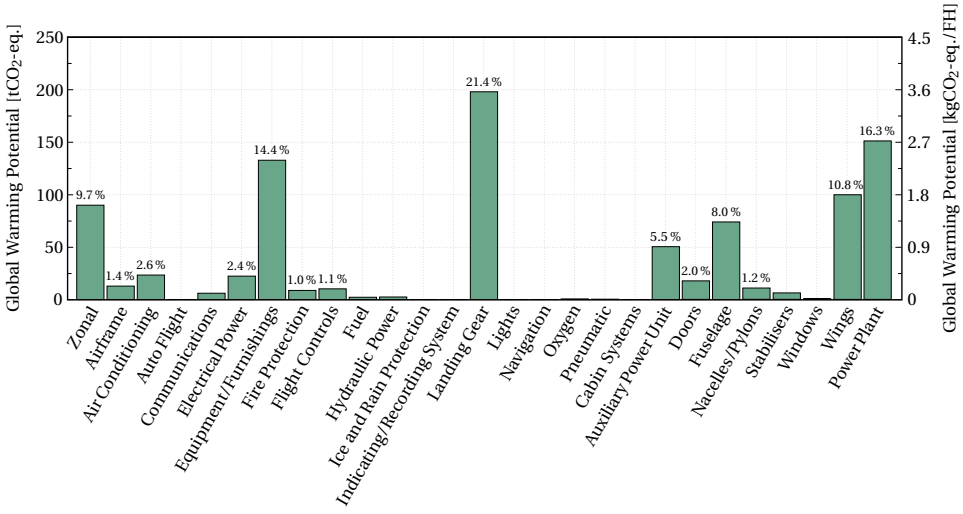


Figure 3.6: Comparison of the environmental impact of maintenance tasks for different ATA chapters in terms of absolute values and normalised per FH. The share of the total impact is additionally indicated for each component for which the contribution accounts for more than 1.0 % of the total share.

The figure illustrates the distribution of environmental impacts, with the landing gear having the highest impact of 198.0 tCO_2-eq., mostly due to regular tyre replacement and landing gear shop visits. Scaled to the functional unit, this amounts to about 3.6 $kgCO_2$-

eq./FH. Similarly, the power plant and APU also contributed to the overall impact, with 150.8 tCO_2-eq. and 50.6 tCO_2-eq., respectively. Equipment and furnishing accounted for a significant portion of the environmental impact with 132.9 tCO_2-eq. and 2.4 $kgCO_2$-eq./FH, mainly because of the cabin replacement, which is typically performed during a D-check. Other notable component groups included air conditioning, electrical power, fuselage, and wings, which all had significant men hour allocations in the MPD. Overall, about 61.1 % of the environmental impact of maintenance activities was attributed to aircraft systems, while tasks related to structural components represented 22.6 %. Maintenance tasks at the power plant accounted only for 16.3 % of the total impact.

Results for Main Environmental Drivers

In this section, a deeper analysis of the LCA results was carried out to gain a more thorough understanding of the environmental impact of MRO. This detailed examination of each maintenance task and its accumulated impact over the entire life cycle has enabled the identification of the main contributors with the greatest ecological impacts. The results provide valuable insights for stakeholders in the aviation industry to highlight the biggest reduction potentials and to develop and implement effective measures to reduce their environmental footprint. Figure 3.7 provides an overview of the identified main drivers of the ecological implications and their share of the overall impact.

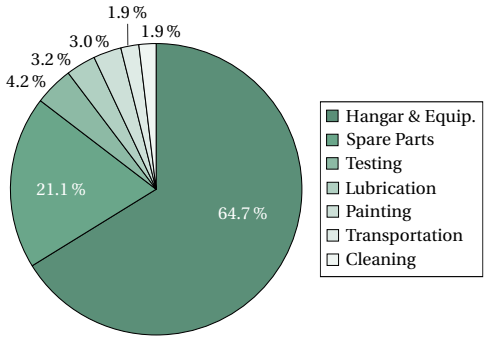


Figure 3.7: Distribution of the main drivers of the ecological implications.

The distribution reveals that the overall environmental impact is dominated by energy-intensive maintenance processes rather than by consumables or individual maintenance tasks. Energy consumption for the operation of hangars and equipment accounted for approximately two thirds of the total environmental impact, making it the largest contributor. An average German energy mix was used as a baseline for the assessment of electricity consumption. The discard and replacement of components, including filter elements and major spare parts, contributed 21 % of the impact. Other factors, such as the operation of test benches that follow specific maintenance procedures (especially for engines) or the repainting and cleaning of components represented only a minor share of the total ecological impact.

3.4.2.2. Other Impact Categories

Below, a detailed examination of additional impact categories at check-level is presented to gain a more detailed understanding of the environmental implications. Here, we focus specifically on three additional impact categories: Freshwater Ecotoxicity (FETP), ODP, and MM. The results of all impact categories can be found in the supplementary data.

A direct comparison (Figure 3.8) shows that, although the daily check had the highest impact in the impact category of FETP, it did not dominate in the other categories. In particular, in the ODP, the D-check emerged as the most significant contributor, mainly due to the extensive cabin replacement and repainting activities. In contrast, both A-check and D-check had a significant impact on the MM category, largely due to the frequent tyre changes and the aforementioned D-check activities. In comparison, the C-check had the lowest environmental impact of all line and base maintenance checks. When looking at the combined environmental impact, line maintenance emerged as the dominant contributor in almost all categories, with the exception of ODP. The impact varied significantly across the categories, ranging from 33.7 % to almost 80 %. Conversely, shop maintenance generally had the lowest impact in the analysis, with the highest contribution of just over 19 % in the MM category. This notable impact in MM was mainly because of the extensive use of spare parts and related materials.

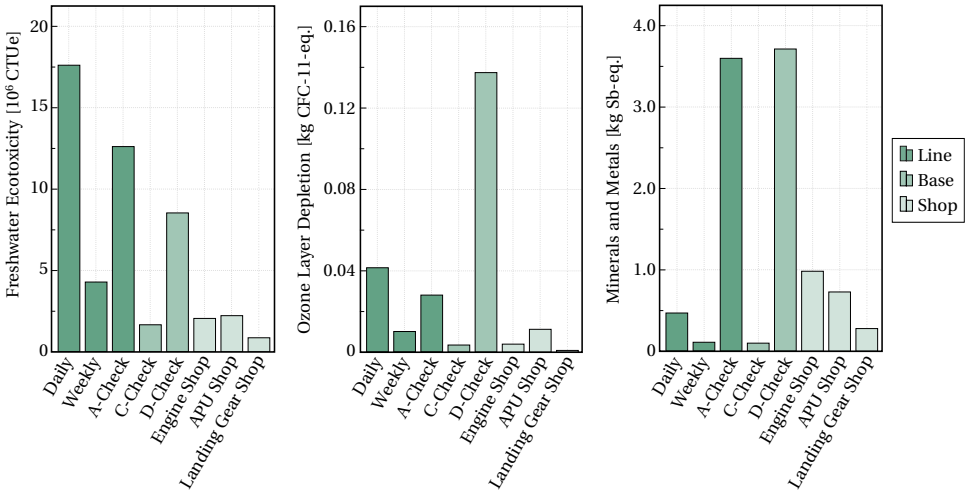


Figure 3.8: Comparison of LCA results for the impact categories FETP (left), ODP (middle), and MM (right). The bars are divided by colour into line, base, and shop maintenance.

3.4.3. Scenario Analysis

The frequency of maintenance tasks performed is strongly influenced by the operator's usage. Different operational scenarios [142] can be used to represent various ways in which the Airbus A320 class aircraft is used. The reference flight profile consisted mainly of short-haul flights with an average distance of approximately 741 km. In addition to

this, another flight plan with long-haul flights (with an average distance of approximately 1,286 km) was analysed. The short-haul and long-haul schedules were simulated using two different business models (FSNC and LCC) resulting in a total of four different utilisation scenarios. Table 3.5 provides an overview of these scenarios, including the corresponding FC and FH per year.

Table 3.5: Overview of utilisation scenarios from [142].

Scenario	Business Model	Flight Profile	FH/Year	FC/Year
Reference	FSNC	short-haul	2,200	1,920
Scenario 1	LCC	short-haul	2,530	2,219
Scenario 2	FSNC	long-haul	2,800	1,421
Scenario 3	LCC	long-haul	3,320	1,885

Figure 3.9 shows the GWP in tCO_2-eq. for each check in each scenario, accumulated over a full lifetime of 25 years. In our analysis, the D-check was performed at fixed intervals of six years, resulting in no deviations compared to the reference. Similarly, the daily and weekly checks showed minimal variation as they followed fixed calendar intervals. The minor differences between them were due to their inclusion in other checks, resulting in slightly more or less frequent execution. The pattern was different when looking at tasks linked to FHs and FCs. If an operator mainly operates long-haul flights, maintenance tasks connected to flown hours will be performed more frequently, resulting in a greater environmental impact. This was evident in the case of the A-check, C-check, and certain tasks during the engine and APU shop visit. Conversely, since the landing gear shop maintenance was only twice in the aircraft's lifetime, there was no variation between the different scenarios.

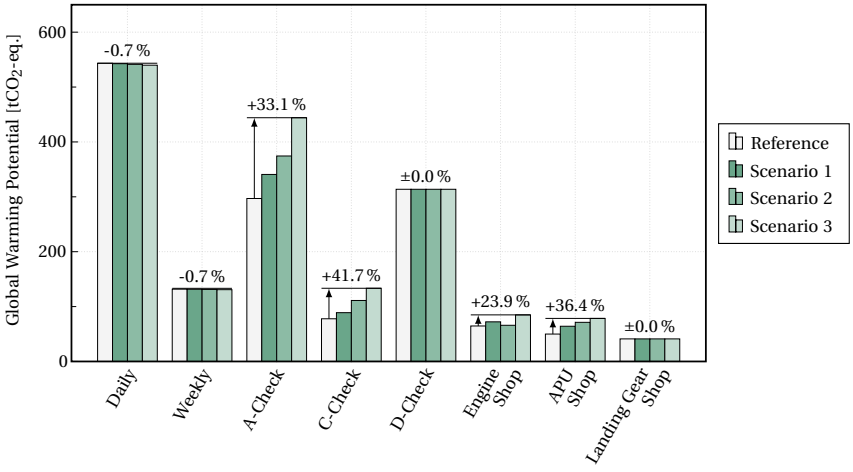


Figure 3.9: Overview of the ecological impact (given in GWP) including the largest deviation from the reference case for each scenario (Reference: FSNC/short-haul; Scenario 1: LCC/short-haul; Scenario 2: FSNC/long-haul; Scenario 3: LLC/long-haul).

To facilitate comparison between flight scenarios, the results were normalised in terms of FHs and ASK. The results for each scenario are shown in Table 3.6. The reference case (FSNC with short-haul) had, even though having the lowest total environmental impact, the highest ecological implication per flown hour with 28.3 $kgCO_2$-eq./FH, closely followed by LCC with a short-haul flight profile. Both flight scenarios with long-haul schedules led to lower environmental impacts, with 24.2 $kgCO_2$-eq./FH for the FSNC and 21.9 $kgCO_2$-eq./FH for the LCC. The higher environmental impact of the maintenance with short-haul flight schedules was mainly due to the significantly higher number of FCs over the life cycle of the aircraft and the more rapid degradation of LLPs.

Table 3.6: Overview of results for the considered flight scenarios.

Scenario	**Global Warming Potential**		
	[tCO_2-eq./lifetime]	[$kgCO_2$-eq./FH]	[$kgCO_2$-eq./ASK]
Reference	1,555	28.3	2.9×10^{-4}
Scenario 1	1,635	25.8	2.7×10^{-4}
Scenario 2	1,692	24.2	2.5×10^{-4}
Scenario 3	1,815	21.7	2.2×10^{-4}

In addition, the environmental value is provided in ASK in the last column of Table 3.6. The ASK normalises the environmental impact per flown kilometre per passenger seat over the lifetime of the aircraft. This unit is often used in environmental assessments of aviation [141] and is therefore suitable for comparison with other studies. It also facilitates comparison with other modes of transport, such as cars or trains, as it includes the maximum number of passengers in the environmental value.

3.5. Discussion

The results of this study provide insights into the environmental impact of aircraft maintenance and give an overview of potential improvements at check-level as well as component-level. Despite their relatively short duration, daily checks were found to have the largest overall impact due to their daily occurrence and contribute alone to more than one third of the total environmental impact in terms of GWP. Although the environmental impact of an individual daily check is comparatively small, its very high frequency over the aircraft lifetime, together with the repeated operation of diesel-powered GSE, results in the highest cumulative environmental impact of all maintenance checks. Introducing longer service intervals for these kinds of maintenance activities may be an effective strategy for more sustainable MRO practices and could significantly reduce the environmental impact. In addition, the D-check, including cabin removal and repainting, was shown to be another major contributor to the overall impact. Future research efforts could focus on developing more durable furniture and coatings, and exploring the use of sustainable materials. The same is true for A-checks, where regular tyre replacements due to safety reasons introduce a big ecological impact because of the re-manufacturing of these tyres.

Our analysis at ATA chapter-level identified specific components that offer significant potential for further research, such as the landing gear or power unit. This is consis-

tent with studies that have looked at the economic impact of maintenance for individual aircraft components. Using a cost-estimating model for aircraft maintenance, Fioriti et al. [159], for example, showed that the landing gear is by far the component with the highest maintenance cost at over 76 $/FH, being consistent with the present study.

A closer look at the main drivers of the ecological impact shows that more than 66 % of the ecological footprint is contributed by the electricity required for lighting and heating or cooling the maintenance hangar and equipment. This represents a large reduction potential, e.g., by supplying the MRO facilities with renewable energy sources or by reducing energy consumption in general. In addition, due to the scarcity of aircraft materials and the large number of spare parts needed throughout the life of an aircraft, MRO providers as well as aircraft manufacturers should be encouraged to focus on research into extending the life of these components and improving the recyclability of materials, which could bring significant economic as well as environmental benefits.

However, there are several limitations in this study. Firstly, the limited number of comparable studies highlights the need for further research to validate the results and gain a better understanding of maintenance activities in general. In addition, this study only considered scheduled and routine maintenance for the calculation of environmental impacts. Other studies evaluating aircraft life cycle maintenance indicate that the economic costs of unscheduled maintenance are significantly higher, by a factor of up to 2.5 times, than scheduled maintenance [160]. Future studies should therefore include additional unscheduled factors. In addition, the workshop visit activities were challenging to assess due to limited data availability, despite their significant contribution to the overall impacts. The ecological impact of shop visits could account for a much higher proportion of the overall impact than calculated here. Estimations were made when considering certain materials and masses as well as the intervals between different maintenance activities. Maintenance checks or tasks in the MPD usually have not one but several thresholds that the operator or MRO provider has to consider. This may lead to variations in the occurrence of tasks and checks.

The detailed MPD analysis is also not applicable on its own, as it does not include all maintenance activities and does not provide information on the operation of the hangar or the equipment, as the planning and clustering of simultaneous maintenance activities is the responsibility of the operator. In addition, various assumptions had to be made in order to model the LCI. For example, the choice of maintenance location has a significant impact on the environmental impact, as it depends largely on the regional energy mix. The lack of aircraft-specific data in conventional LCI databases introduces further uncertainties, which we partially addressed by introducing an aerospace specific titanium alloy. Future studies could focus on providing more aerospace specific LCI data to enhance existing LCI databases. Depending on the chosen LCIA indicator, the results and their subsequent implications may vary, posing additional challenges, particularly when disseminating the results to different stakeholders.

3.6. Summary and Outlook

This study presented a novel approach for conducting a comprehensive LCA of aircraft maintenance, using the case study of an Airbus A320 aircraft. Compared to other studies

in the literature, this research method allows a much higher level of detail to be obtained. The results of the combined top-down approach and detailed analysis of the MPD provide valuable insights into the environmental impacts of aircraft maintenance and contribute to a more holistic understanding of the aircraft life cycle. While the check-level analysis provides a broad perspective on the overall environmental impact of maintenance, the detailed MPD analysis enables a more granular understanding of individual tasks. By breaking down maintenance activities into components and component groups (based on ATA chapters), this method enables the identification of components with the highest environmental impact associated with maintenance. The adaptability of this approach to different aircraft types and new maintenance tasks is a major strength. For the comparison with existing aircraft, the integration of existing or advanced MRO activities and intervals as well as multiple flight schedules into the LYFE model allows the simulation of environmental impacts over any given lifespan. In addition, a detailed analysis of new technologies, including their durability and shortcomings, enables the development of appropriate maintenance tasks. These findings can be used to target improvements in environmental performance when evaluating new aircraft concepts.

Although the impact of aircraft maintenance on the overall environmental footprint during the aircraft life cycle accounts is rather small (about 1 %), it remains a crucial part of aircraft operation. As aircraft technologies evolve to reduce in-flight emissions, the share of maintenance in the overall environmental footprint will grow. This is especially true for aircraft currently under research, which are both zero-emission in the use phase and are projected to have higher maintenance demands [12]. Therefore, transparency of the ecological footprint of individual MRO operations is crucial to establish a baseline against which innovations in maintenance can be evaluated. Additionally, maintenance is integral to regulatory compliance and ecological responsibility across the aircraft's life span. We note that advancing maintenance practices to minimise aviation's environmental footprint must be closely aligned with economic and social considerations that were out of scope in the current work.

Overall, this study highlights the importance of including aircraft maintenance activities in LCA studies, including the incorporation of specific aircraft materials or processes. The approach presented here provides valuable insights for researchers, industry practitioners, and policy makers to prioritise sustainability measures and improve the environmental and economic performance of aircraft throughout their life cycle. For future work, it is intended to adapt the developed methodology to other aircraft types - in particular to new aircraft concepts, such as hydrogen-aircraft. A study of the economic and environmental trade-offs could therefore be of particular interest.

Chapter 4

Quantifying Climate Impacts of Flight Operations: A Discrete-Event Life Cycle Assessment Approach

With initiatives such as the European Green Deal establishing more stringent environmental requirements, there is an increasing need to develop aircraft technologies and sustainable aviation practices with reduced climate impacts. Additionally, conventional environmental life cycle assessments often struggle to capture the dynamic and complex nature of aircraft operations; in particular, non-CO_2 in-flight impacts, which contribute significantly to climate change, are often overlooked. In this study, we improve a discrete-event life cycle assessment approach with a climate impact evaluation model and apply it to scenario analyses comparing different aircraft designs, fuel types, and flight schedules. Our findings reveal that, contrary to previous life cycle assessment studies, the climate impact per kilometre flown increases with longer flight distances and that an efficiently planned flight schedule can reduce the overall environmental impact. The study highlights the necessity of incorporating non-CO_2 effects and operational scenarios into life cycle assessment to achieve a more accurate understanding of aviation's environmental impact.

This chapter is based on:
Rahn, Antonia; Dahlmann, Katrin; Linke, Florian; Kühlen, Markus; Sprecher, Benjamin; Dransfeld, Clemens; Wende, Gerko. "Quantifying Climate Impacts of Flight Operations: A Discrete-Event Life Cycle Assessment Approach". Transportation Research Part D: Transport and Environment 141, 2025. DOI: 10.1016/j.trd.2025.104646.

4.1. Introduction

Globally, the transport sector is a significant contributor to GHG emissions, with aviation accounting for approximately 2-3 % of global CO_2 emissions [161]. These environmental impacts are particularly hard to abate because aircraft are highly optimised, complex systems that operate under a wide range of conditions and have long lifespans. Unlike other sectors, such as energy and ground transportation, where decarbonisation efforts have made rapid progress, aviation remains one of the most challenging industries to decarbonise owing to the difficulty of implementing technological solutions [162]. The International Energy Agency [163] identified aviation as one of the main sectors that make it more difficult to eliminate fossil fuels to achieve net zero emissions by 2050, which can only be offset with techniques such as direct air capture with carbon capture and storage.

Moreover, aviation is a very complex and diverse industry. The interaction between individual flights and maintenance events throughout the entire life cycle is influenced by numerous external factors, including flight operation planning and maintenance constraints. Furthermore, new fuel types such as SAF have been proposed to change the status quo. To understand the pathways towards a sustainable aviation industry, it is imperative to gain insight into the interrelationships among these diverse elements. Operational improvements such as optimised flight routes can, for example, increase the efficiency of aircraft on certain flight segments. Furthermore, maintenance activities can result in optimised fuel performance, while at the same time, these activities can have an indirect impact on the environment [164, 165].

LCA is a commonly used method for investigating and analysing the ecological impacts of aircraft [18, 44, 166]. However, this method often relies on aggregated data and lacks flexibility, which can lead to oversimplification, particularly when evaluating minor modifications to aircraft [20]. For example, LCA practitioners and industry stakeholders often lack the expertise to convert raw data into structured datasets, as they tend to focus on economic rather than environmental performance indicators. In addition, streamlined assumptions and incomplete datasets for flights can limit the depth of analysis and compromise the accuracy of conclusions [25]. These challenges can result in various issues, such as limited comparability, reduced accuracy of the results, data quality concerns, and increased uncertainties [167]. Despite ongoing research on the significant impacts of flight operations, most traditional LCAs generally do not include information on the exact locations of the emissions or non-CO_2 effects, such as contrail formation and the release of NO_X, which increase radiative forcing and differ from the long-term impacts of CO_2 emissions [168]. However, these effects can account for up to two thirds of aviation's overall climate impact, highlighting their significance and the need for careful consideration [169]. The quantification of non-CO_2 impacts necessitates comprehensive knowledge of aircraft trajectories, engine parameters, and atmospheric conditions [170]. Furthermore, standard LCIs often fail to incorporate necessary aircraft-specific impacts, which are particularly important in the context of novel fuels, new aircraft concepts, and maintenance optimisation [18].

This study combines a discrete-event LCA approach with a climate impact evaluation model that can assess environmental effects at flight-level. The discrete-event LCA breaks down the complex aircraft life cycle into manageable segments and evaluates each phase,

including production, maintenance, flight operations, and end-of-life. This enables a more detailed temporal analysis and identification of the events that are the most environmentally crucial. Additionally, it facilitates adaptation to different flight schedules. The climate impact is analysed via an atmospheric response model that incorporates information on route trajectories, flight altitude, and fuel consumption for each flight. This offers insights into both CO_2 and non-CO_2 effects. The methodology is applied in a comparative analysis that includes various scenarios for conventional turbofan aircraft and turboprop aircraft. The aim of this analysis is to explore the environmental differences across various areas: (1) aircraft designs with different combustion technologies, flight characteristics, and maintenance constraints; (2) the climate impacts of individual flights associated with the use of fossil kerosene and Power-to-Liquid (PtL); and (3) the effects of different aircraft-specific flight schedules. The novelty of this study lies in the detailed comparison of aircraft and their performance, as well as the integration of non-CO_2 effects to assess the climate impact of flight operations.

The remainder of this chapter is structured as follows: Section 4.2 covers the fundamentals of flight operations and their environmental impact. Existing studies are reviewed to identify the current state of the research and gaps in knowledge. Section 4.3 provides the goal and scope definition, along with the LCI generation and a detailed description of the coupled assessment method. In Section 4.4, we present, analyse, and interpret the results of the scenario analyses in greater detail, followed by a concluding discussion (Section 4.5). Finally, Section 4.6 provides a summary of the chapter and topics for future studies, for example, examining the integration of novel technologies.

4.2. Fundamentals

This section introduces the fundamentals of flight operations that are relevant for this study. Building on these technical aspects, the current state of research on LCA studies of flight operations as well as the challenges in integrating climate impacts is reviewed.

4.2.1. Flight Operations

In flight operations, numerous processes and decisions are important for ensuring that flights are carried out safely and efficiently. The following key environmental aspects have been identified on the basis of relevant studies [8, 168, 171]:

- Combustion technology, which significantly influences both the CO_2 and non-CO_2 effects impacting the climate;
- The production and distribution of energy carriers, including conventional and alternative fuel types, which are essential for powering aircraft;
- The planning and scheduling of flights, considering route optimisation and fuel efficiency;
- Regular maintenance and overhaul activities, which are essential for ensuring safety and adhering to airworthiness standards.

While a detailed literature review on the environmental impact of maintenance was carried out by Rahn et al. [172], this chapter provides a basic overview of the remaining

aspects. Despite the relatively small environmental impact of maintenance compared with in-flight emissions, its importance is expected to grow as aircraft technologies shift towards minimising operational impacts.

4.2.1.1. Combustion Technology

Fuel efficiency and, consequently, climate impact are highly dependent on combustion technology [173]. The two most common propulsion technologies for commercial aviation are turbofan and turboprop engines [174]. Turbofan engines are commonly used on medium- and long-haul flights because of their optimal balance between cruising speed and fuel efficiency [175]. In contrast, turboprop engines are most efficient in short flights with lower cruising altitudes, as they result in less time spent in the climbing phase, when aircraft typically have the highest fuel consumption rate. This leads to approximately 20 % higher efficiency than regional jets [176], but their performance decreases at higher flight speeds and altitudes. Despite this trade-off, they typically achieve higher bypass ratios and lower fuel consumption per kilometre flown [1, 177], while their design characteristic is accompanied by longer flight durations and higher noise levels [178].

Comparative environmental assessment studies of turboprop and turbofan aircraft are rare, as turboprop emission indices are often found only in confidential databases, and their dependence on atmospheric conditions is not well understood [179]. Furthermore, the fact that they typically operate in different flight profiles and at different speeds makes a comparison even more challenging. Graham et al. [180] asserted that fuel savings of 13 % or more could be achieved by using turboprop-powered aircraft for all flights shorter than 1,000 km worldwide, even though this could increase travel times and lead to low passenger satisfaction.

4.2.1.2. Sustainable Aviation Fuels

One approach to reducing the environmental impact of flight operations is to use SAF [181]. SAF can be synthesised through various processes, including Fischer-Tropsch, hydroprocessed esters and fatty acids, and alcohol-to-jet pathways [8]. These methods rely on biological and renewable feedstocks, such as agricultural residues and nonfood crops. According to the International Air Transport Association (IATA) [182], SAF has considerable potential to reduce CO_2 emissions from aviation, making it a key component of strategies for decarbonising the industry. Despite its versatility in applications, blending options, and production methods [1], SAF has several disadvantages and challenges. For example, the production of SAF requires significant water resources, which can lead to water shortages, especially in dry regions. Moreover, the cultivation of crops needed for SAF often leads to a direct or indirect change in land use. Such a land use change can lead to deforestation, loss of biodiversity, and soil degradation [161].

PtL, a specific application of the Fischer-Tropsch process for the production of SAF, is described as one of the most environmentally-friendly options and is the most suitable for civil aviation [1, 183]. The Fischer-Tropsch process is a well-established chemical conversion process that synthesises hydrocarbons by converting synthesis gas into liquid fuels. The synthesis gas is produced exclusively from green hydrogen (by electrolysis with renewable electricity) and CO_2 (from sequestration or air capture) [184]. This method

avoids the use of fossil resources and maintains CO_2 in the cycle. Furthermore, it requires less land and water than biomass fuels [185]. Notably, for medium and long distances, PtL fuels present a promising solution [116] because of their reduced high-altitude climate impacts and local emissions resulting from their cleaner combustion process.

Despite the advantages of PtL, relatively few studies have investigated its impact on the environment. This is primarily because PtL is a new fuel type that requires significant process optimisation and scaling before commercialisation [186]. Estimations of GHG emissions for PtL vary widely in the literature, ranging from 1 to 28 gCO_2-eq. per megajoule, depending on the electricity mix [187–189]. Compared with other SAF production technologies, PtL generally has a lower environmental footprint, especially when it is produced using renewable energy sources [190, 191]. However, there may be burden-shifting effects from GWP to other environmental indicators, particularly in terms of water, resource, and energy-related impacts [116]. For example, although the water consumption of PtL is typically higher than that of conventional fossil fuels, it remains significantly lower than that of other SAF fuels [187]. Despite promising environmental benefits and technological advances, PtL fuels are currently not yet fully certified as drop-in capable, as ongoing approval procedures for jet engines must still be carried out [168]. However, the Fischer-Tropsch process allows the production of high quality jet fuel with properties similar to those of conventional kerosene, making it suitable for use in existing aircraft engines and fuel infrastructure without major modifications.

4.2.1.3. Flight Scheduling

Aircraft with turbofan and turboprop engines are best suited for different flight routes. While turboprop engines demonstrate advantages with shorter flight distances owing to their superior propulsion efficiency at lower altitudes and speeds (Mach numbers), turbofan engines offer higher cruise Mach numbers, particularly on longer flights [1, 192]. An efficient flight plan significantly contributes to overall operational performance, which in turn can lead to lower fuel consumption and reduced emissions [193].

While flight planning is essential for operators, few studies in the literature address environmental effects in airline planning and scheduling. Strategies for reducing overall emissions include the optimisation of flight speed, which can lead to a reduction in fuel consumption and therefore emissions, and the elimination of flights with low load factors [194–196]. Furthermore, an improved combination of direct and connecting flights [194, 197] and the restriction of flight altitude [198, 199] can further contribute to the sustainability of flight operations. As an example, the study of Noorafza et al. [200] developed a multi-objective framework for airline network planning that demonstrated potential in climate change mitigation. The results of this framework indicate that efficient network planning can reduce the climate impact by 10-36 % when aircraft are allocated to shorter routes at lower altitudes. This is related to the fact that flights at lower altitudes have a lower climate impact, as the warmer temperatures at lower altitudes result in fewer or no long-lasting condensation trails that could contribute to warming at the surface [201]. However, there is a trade-off between climate protection and profitability for the operator, as climate-optimised re-routing can result in longer flight times, increased fuel consumption, and higher operating costs [202].

4.2.2. Life Cycle Assessment of Flight Operations

This section reviews existing approaches for assessing flight operations within conventional LCA studies and discusses their limitations. Particular attention is paid to the consideration of non-CO_2 effects and the selection of appropriate climate indicators, which remain key challenges in aviation-specific environmental assessment.

4.2.2.1. Overview of Existing Life Cycle Assessment Studies

The assessment of flight operations in LCA is typically based on data on fuel consumption and emission factors. A frequently utilised reference is the inventory guidebook by the European Environment Agency and the European Monitoring and Evaluation Programme [203], which provides emissions for each Landing to Take-Off (LTO) cycle as specified in accordance with the ICAO [204]. Although numerous studies distinguish between individual flights with LTO and cruise phases to account for different flight distances, they often rely on data from a single average flight extrapolated to the aircraft life cycle [37, 205]. Other studies employ emission databases such as the Emission Data Modelling System [53, 129], the Aviation Environmental Design Tool [206], the Intergovernmental Panel on Climate Change (IPCC) database [52, 131], the Piano-X database [207], and the ecoinvent database [51, 57]. All of these databases lack specific life cycle emission factors for new fuel types and their various production paths [204].

The literature emphasises that the climatic effects of in-flight emissions must be assessed differently than ground-level impacts. The studies of Cox et al. [29] and Johanning & Scholz [35] demonstrate that impacts such as those of NO_X emissions and contrails are altitude-dependent and thus can be included in the assessment only via enhanced LCA methods. The study of Cox et al. [29] employs LCA in conjunction with climate impact assessment by separately modelling the exhaust emissions for the LTO and cruise phases and including the GWP impacts resulting from aircraft CIC formation. The climate effects during flight operations are calculated via characterisation factors obtained from Fuglestvedt et al. [208]. The CO_2 uplift factors used here vary on the basis of the flight distance and can therefore result in an over- or underestimation of the ecological impact. Johanning & Scholz [35] extended the ReCiPe LCIA methodology to include the altitude-dependent climate impacts of NO_X emissions and contrails. Therefore, the authors used the sustained Global Temperature Potential (GTP), an alternative to GWP, for the comparison of emissions concerning their impacts on climate, which takes into account the long-term temperature effects of emissions. The results showed that flying at lower altitudes is a key design criterion, in addition to low fuel consumption. One limitation of the study is that it only considered altitude, not distance.

In recent years, there has been a significant increase in LCA studies examining the environmental impacts of PtL fuels [116, 209, 210]. These studies show that the environmental footprint of PtL fuels is largely influenced by the considered production pathways and the type of renewable energy sources used. The most commonly analysed environmental impact categories include CC, land use, water consumption, and electricity demand [211], as they capture the most important environmental aspects across the entire PtL fuel value chain. With respect to the CC impact category, PtL fuels can achieve an approximately 50 % reduction in CO_2 equivalents compared with conventional kerosene [187]. The re-

duction potential varies according to the length of the flight, with reductions ranging from 44 % for short-haul flights to 56 % for long-haul flights [212]. A study by Micheli et al. [188] reported potential emission reductions of up to 88.9 % with non-CO_2 effects being excluded.

4.2.2.2. Challenges in Integrating Climate Impacts

While existing LCA studies provide valuable insights into the environmental impacts of the whole aircraft life cycle, they face limitations in incorporating non-traditional climate-relevant effects that are influenced by a range of factors, including flight altitude, weather conditions, and flight routes. In particular, non-CO_2 effects are often overlooked, despite their significant impacts on the climate. These effects include contrail formation, ozone generation, and aerosol interactions, with some of these effects occurring only in higher atmospheric layers [169]. Their non-linearity in relation to CO_2 and their spatial and temporal variability make the assessment of non-CO_2 effects highly uncertain [213]. Proper consideration of these effects is crucial, as they can substantially influence the overall climate impacts of various activities, especially in sectors such as aviation.

For example, aviation emissions released at cruise altitudes of 812 km lead to complex climate-relevant effects, including non-linear atmospheric chemistry induced by NO_X emissions and the formation of CIC [214, 215]. These processes complicate the prediction and modelling of aviation climate impacts [214, 215]. The non-CO_2 effects and their interactions with other atmospheric components are difficult to measure, and scientific models are required. However, the integration of these elements into standardised LCA methodologies remains challenging owing to the limited flexibility of these methods and their inability to reflect short-term and regional climatic differences [20].

There are various approaches and metrics for assessing the climate impact of aviation, and which of these should be selected strongly depends on the objectives of the assessment [216]. The majority of climate metrics are based on either radiative forcing or temperature change, including GTP and ATR [217]. The most commonly employed indicator for assessing climate change is GWP. However, GWP has certain limitations in regard to the assessment of air transportation [162, 218, 219]. One limitation is that the application of GWP to short-lived emissions, such as NO_X emissions and their contribution to ozone formation, is associated with considerable uncertainties and depends heavily on the emission source and atmospheric conditions [220]. Furthermore, conventional LCIA do not include contrails in the estimate of CO_2-eq., which may result in an underestimation of the radiative forcing caused by aircraft [221]. Nevertheless, GWP is widely accepted in various climate policy contexts and is often used in emission reports, climate targets, and international agreements [169, 208]. Its widespread acceptance is due to its simplicity, transparency, and comparability, making it a practical choice for decision-makers and stakeholders. To ensure consistency with existing LCA frameworks and to enable comparability with previous studies and policy targets, GWP is chosen as an acceptable climate impact metric [222]. While alternative metrics, such as ATR, provide a more nuanced representation of short-lived effects and contrails [101, 223, 224], they are not yet widely used in LCA methodologies. Therefore, the use of GWP

enables alignment with established practices while acknowledging its limitations for aviation-specific emissions.

4.3. Method

In the following section, an LCA approach is presented to investigate the environmental impacts of two comparable aircraft designs with different propulsion systems. The goal and scope, including the system boundaries and functional units, are described. This is followed by a detailed description of the LCI generation and the combined discrete-event LCA and climate impact assessment approach.

4.3.1. Goal and Scope

In this study, an LCA is carried out to evaluate the environmental footprint of a product at each stage of its life cycle. It is based on the existing ISO 14040/44 [21, 22] framework, which describes the principles and methods behind the LCA. An LCA can be divided into four stages. In the first stage, the goal and scope of the study are defined, such as the system boundaries and assumptions. In the subsequent LCI, the data for all the inputs and outputs are generated and collected. The third stage of an LCA is referred to as the LCIA. It translates the information from the inventory into existing environmental impact categories. Finally, the results are interpreted, and conclusions are drawn. The LCA methodology is applied to compare the environmental impact of a turbofan-powered aircraft and a turboprop-powered aircraft via three different scenario analyses (see Figure 4.1):

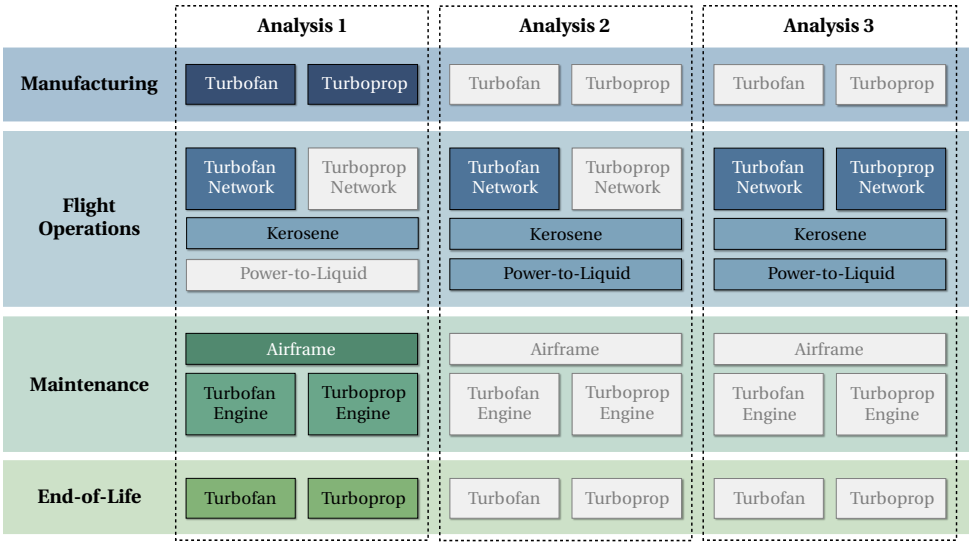


Figure 4.1: Graphical overview of the three analyses performed. The coloured boxes indicate what is included within the system boundaries of each analysis.

(1) In the first analysis, the environmental differences between a turbofan and a turboprop aircraft are analysed throughout their entire life cycles. Both aircraft operate with kerosene and have the same flight schedule. The main differences result from their propulsion systems, which influence both the cruising speed and the flight altitude, as well as their maintenance requirements.

(2) The second analysis compares the flight phases of these two aircraft when flying with two different energy carriers: conventional kerosene and PtL. These two fuel types have different production pathways and combustion properties that affect their environmental impacts.

(3) Finally, a network scenario analysis is performed, in which the turboprop aircraft is additionally operated on a dedicated turboprop flight network. This leads to a flight schedule adjustment with more and shorter flights. A comparison of these different flight schedules shows how the environmental impacts change with respect to different aircraft utilisation profiles.

The analyses of these scenarios at different detail levels illustrate the complexity of this comparative LCA. A detailed description of the individual scenarios and their system boundaries is given below. The results of this study are expressed in the two functional units per lifetime and per ASK, which standardise the environmental impact assessment. Per lifetime denotes the projected aircraft life cycle, from manufacturing to the end-of-life. ASK represents the maximum possible transport capacity, which is calculated as the product of the total number of available seats and the distance flown. In contrast to the commonly employed PAX-kilometre, ASK is independent of the seat load factor. This eliminates the variability caused by differing load factors and allows for consistent comparisons across varying operational scenarios and utilisation profiles. The assessment covers the period from 2040 to 2065, assuming that the aircraft are manufactured and maintained in Germany and operate within Europe. The impact assessment was performed according to the method of Fazio et al. [147] with the EF 3.0 LCIA methodology. The climate impacts for individual flights are calculated with a climate response model in terms of CO_2 equivalents with a time horizon of 100 years. The underlying modelling approach is described in Section 4.3.3.

4.3.1.1. Analysis 1: Comparison of Turbofan and Turboprop Aircraft

Both aircraft designs were developed as part of DLR's EXACT project and serve as reference aircraft for innovative aircraft concepts (e.g., hydrogen-powered and hybrid-electric aircraft). The designs are based on an Airbus A321neo with some minor modifications and an assumed passenger capacity of 250 PAX. The entry-into-service based on the estimated technological advancements is 2040, and the operating lifetime of both aircraft is set to 25 years, in accordance with the ICAO [140]. The OEWs of the turbofan and turboprop aircraft are 44.9 tonnes and 42.3 tonnes, respectively. The two aircraft under consideration are designed on the basis of the same top-level aircraft requirements but differ mainly in their propulsion systems and some aircraft features, such as the wing shape and the T-tail arrangement (see Figure 4.2). The material and mass distributions of the aircraft designs are primarily based on Atanasov et al. [225]. When specific details

were missing, reasonable assumptions were made, as outlined in the supplementary material. The LCA considers all life cycle phases from manufacturing to the end-of-life.

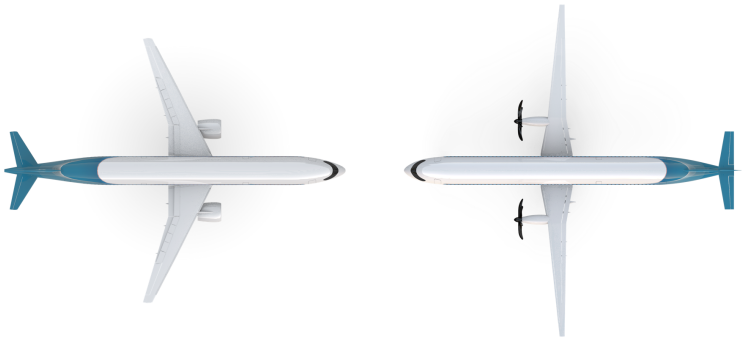


Figure 4.2: Conventional turbofan (left) and turboprop (right) aircraft developed for the DLR-internal EXACT project (source: DLR, internal documentation).

The propulsion systems (turboprop engine versus turbofan engine) differ primarily in their material composition, fuel efficiency (which has an impact on flight operations), and maintenance constraints. The turbofan engine is assumed to represent a conventional CFM56-series engine, which is commonly used in aircraft of the size of the Airbus A321. The turboprop engine was designed on the basis of top-level modelling of the gas turbine and gearbox, along with a propeller model based on blade element theory. The overall geometry of the propeller is similar to that of the Airbus A400M military aircraft. Both aircraft have the same design range of 1,500 NM and operate under the same flight schedule, ensuring comparability. However, the superior fuel efficiency of turboprops at lower altitudes [176] results in a lower fuel consumption than that of turbofan aircraft. Specifically, the turbofan aircraft operates at a cruising speed of 0.78 Mach with a fuel consumption of 4.23 kg/NM, whereas the turboprop cruises at 0.66 Mach and 3.44 kg/NM. Furthermore, the reduced cruising speed of the turboprop aircraft restricts the number of flights that can be completed within a given time period [225].

As the airframe structures of the two aircraft are nearly identical, a unified maintenance plan is created for both aircraft, with only engine maintenance expected to differ. Engines are maintained in regular shop visits, during which they are removed from the aircraft (the aircraft typically receives a spare engine during this time) and taken to a dedicated facility where they are disassembled and inspected, eventually receive replacement spare parts, are reassembled, and undergo a final engine test [226]. The duration of such engine maintenance and the interval between two shop visits can depend on various factors, such as the type of engine, its usage profile, or the life cycles of individual components within the engine (known as LLPs). The two aircraft maintenance schedules are developed according to Rahn et al. [172] and Oestreicher et al. [226]. Table 4.1 gives an overview of the maintenance checks for both aircraft, including their durations and intervals, which are given in FCs and FHs. These activities include not only regular engine shop visits, which vary between hot section inspections (i.e., a detailed examination of components exposed to high temperatures during operation) and more comprehensive full overhauls

of the entire engine, but also the replacement of LLPs. LLPs can consist of a variety of components and are grouped into different modules for simplification. The construction of the facilities and the end-of-life of spare parts are outside the scope of this study.

Table 4.1: Comparison of maintenance activities for turbofan and turboprop engines, including durations and intervals. Due to the upscaling of the turboprop engine, precise data for the shop visit are unavailable, resulting in rough estimations of both durations and intervals [108, 143, 145, 227].

Check	Turbofan		Turboprop	
	Duration	Interval	Duration	Interval
Engine Shop Visit:				
Hot Section Inspection	672 h	5,000 FC	≈ 450 h	5,000 FC
Full Overhaul	1,008 h	10,000 FC	≈ 1,008 h	15,000 FC
Life Limited Parts:				
Fan	-	30,000 FC	-	-
Propeller	-	-	-	≈ 10,500 FH
Low-Pressure Compressor	-	20,000 FC	-	25,000 FC
High-Pressure Compressor	-	20,000 FC	-	30,000 FC
High-Pressure Turbine	-	25,000 FC	-	15,000 FC
Low-Pressure Turbine	-	25,000 FC	-	30,000 FC
Power Turbine	-	-	-	30,000 FC

4.3.1.2. Analysis 2: Comparison of Kerosene and Power-to-Liquid

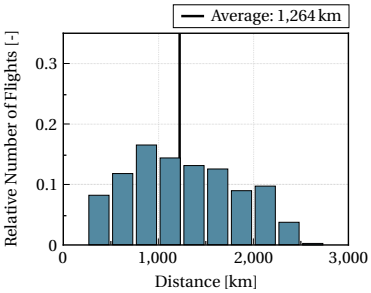
For a more detailed analysis of the different flight characteristics of turbofan and turboprop aircraft, both aircraft are operated with conventional kerosene as well as with PtL. The comparison of these two types of fuel depends on various factors during production and combustion and can, depending on the aircraft propulsion system, lead to large differences in the overall environmental impact. For example, when alternative fuels are used [228], there is less emitted soot, which influence contrail properties and radiative forcing. The climate impact is analysed for each flight in the flight schedule, depending on its trajectories, altitudes, and locations. Fuel consumption per flight is calculated on the basis of the trajectory data, with interpolation applied for intermediate distances. The impact of fuel production includes all processes from well-to-tank. A PtL Fischer-Tropsch production pathway with CO_2 from direct air capture based on van der Giesen et al. [184] was chosen. Wind power was selected as the renewable energy source.

4.3.1.3. Analysis 3: Comparison of Flight Schedules

The two aircraft concepts are designed on the basis of the same top-level aircraft requirements (as specified by Atanasov et al. [225]), with a dedicated design range of 1,500 NM (2,778 km). To facilitate a more accurate comparison, a reference scenario is employed to assess the performance of both aircraft on a common flight network comprising short- to medium-haul flights within Europe that aligns with these top-level requirements. How-

ever, owing to the enhanced fuel efficiency of the turboprop aircraft at lower altitudes (i.e., for shorter flight distances), operation on the same flight schedule does not fully reflect the potential of the turboprop aircraft. As a further improvement, the turboprop aircraft is additionally operated on a second network, which is adapted especially for turboprop engines with shorter distances, lower velocities, and a greater number of flights.

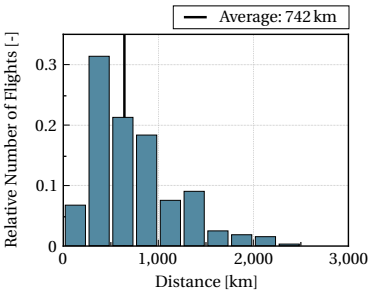
Both flight schedules are generated based on global air traffic data, aircraft characteristics, and a global fleet assignment model. This model assigns aircraft to flight routes based on their performance characteristics (e.g., range, speed, and operating cost) while considering operational constraints of the airline [229]. The sequences of representative routes are then aggregated into the two flight schedules. As the fleet assignment methodology is beyond the scope of this study, only the resulting flight schedules are considered here. A detailed description of the flight schedule generation is provided by Kühlen et al. [229]. The resulting turbofan flight schedule combines 1,589 inter-European flights per year with an average distance of 1,264 km. The turboprop flight schedule consists of 1,881 flights annually over an average distance of 742 km. Figure 4.3 shows the flight distance histograms and the geographical distributions of the two flight schedules.



(a) Turbofan flight distance histogram.



(b) Turbofan geographic distribution.



(c) Turboprop flight distance histogram.



(d) Turboprop geographic distribution.

Figure 4.3: Flight distance histograms and geographical distributions of the two flight schedules.

4.3.2. Generation of the Inventory

The LCI generation is based on the background ecoinvent database version 3.9.1, with the cut-off by classification system model [146]. The foreground inventory for the aircraft was

derived from Rahn et al. [141] and adjusted to align with the two aircraft designs. Datasets for specific aircraft materials (such as aluminium and titanium alloys) were created on the basis of Oestreicher et al. [230] using their defined material composition. The energy required for the raw material extraction and alloying processes of these materials was modelled based on their melting enthalpies. Heat losses due to the furnace efficiency was assumed to be 29.5 % [231]. The energy for casting, forging, and machining of the materials is taken from literature with buy-to-fly ratios of 2.5 for casting [232] and 2.4 for forging [233]. As turboprop engines are only used commercially in smaller aircraft, there is no material or mass breakdown available for engines of this size. For this reason, we created a computer-aided design model of a PW100 turboprop engine with its individual components and scaled them on the basis of the thrust and propeller specifications. The LCIs for aircraft maintenance were taken from Rahn et al. [172] and adapted for the two engine types. Information on engine maintenance was collected and combined from various sources [108, 226, 227]. Whenever electricity was included in the inventories, a German energy mix was used. The end-of-life impacts were generated for the two aircraft via the credit for avoided burden method [112]. This approach quantifies the energy savings that are achieved through recycling and re-use compared with the production of virgin materials as well as the energy recovered via incineration. The aggregated LCIs and the underlying assumptions can be found in the supplementary data.

The inventories for flight operations are twofold. Regarding fuel production (kerosene and PtL), an LCI is prepared on the basis of the literature. The inventory for the production of kerosene is taken from the ecoinvent dataset *market for kerosene* (in Europe without Switzerland). Regarding the production of PtL, the inventory is modelled based on van der Giesen et al. [184]. The energy for green hydrogen production is generated from wind power in Germany, which is evenly split between 50 % onshore and 50 % offshore contributions [234]. The climate impact during in-flight operations is calculated individually for each flight in the schedule, which requires a corresponding flight profile. This flight profile includes the emissions along a trajectory and is mapped via the great-circle connections to create an emission inventory by superposition. In addition to the quantity of emissions, the geographical location and altitude are captured in this dataset. The non-CO_2 effects are determined on the basis of the concentrations of H_2O, NO_X, and CIC across different atmospheric regions [235]. Interested readers are referred to Dahlmann et al. [170] for more information. Because the trajectory is simulated in discrete range steps of 100 NM (approximately 185 km) [236], all flights with distances of less than 200 NM for the turbofan and 100 NM for the turboprop are extrapolated. Individual emissions and their resulting climate impacts are attached as attributes to each flight in the schedule.

The data used to generate the LCI are selected on the basis of five key dimensions (reliability, completeness, temporal correlation, geographical correlation, and technological correlation, based on Ciroth et al. [237]) and qualitatively evaluated to identify potential limitations. To address the uncertainties in our approach, a sensitivity analysis is illustratively conducted for propeller replacement in the turboprop engine. In addition to assuming replacement during every engine overhaul, we consider scenarios in which the propeller is only replaced during every second or third overhaul.

4.3.3. Combined Life Cycle Assessment and Climate Impact Evaluation

The environmental assessment is carried out via a combined discrete-event LCA approach and a climate impact evaluation. The LCA is performed with the Python-based evaluation framework LYFE, which is based on a discrete-event simulation environment that models the aircraft life cycle. Discrete-event simulation is a computer-based modelling technique used to analyse dynamic systems whose states change only at discrete points in time [238]. These changes are triggered by events that occur in the system at specific time instants. It is often used in modelling complex processes, particularly in the areas of production, logistics, health care systems, and transport. Owing to the complexity associated with discrete-event simulations, they have rarely been applied to environmental issues [70]. In combination with LCA, discrete-event simulation can overcome some of the problems of traditional LCA, such as its static behaviour and the lack of detail in the modelled processes [71, 141]. This approach enables the analysis and simulation of different life cycle phases, including production, individual flights, maintenance events, and end-of-life scenarios. By sequencing individual events based on their dependencies, LYFE provides insights into relevant operational factors. This allows a direct analysis of improvements within the product life cycle and supports the decision-making process. A detailed description of the discrete-event simulation framework LYFE, including its capabilities, requirements, and overarching goals, can be found in Pohya et al. [85]. The framework can be further extended to include environmental assessment, as detailed in Rahn et al. [141, 172]. An independent LCA based on the generated inventory explained in Section 4.3.2 is performed for each event and then aggregated over the whole life cycle. The integration of environmental attributes into the discrete-event simulation framework allows for the simultaneous evaluation of both economic and environmental aspects. This enables, for example, the simulation and analysis of the effects of different operating parameters or flight schedules over the entire life cycle of the aircraft. One of the new features of LYFE is the integration of climate impacts for single flights.

The flight trajectories and their corresponding emissions are calculated via DLR's internal tool Global Air Traffic Emission Distribution Laboratory (GRIDLAB), with the Trajectory Calculation Module (TCM) as the core element [239]. The climate impact of in-flight emissions is then assessed with the climate response model AirClim. As described by Dahlmann et al. [101] and Grewe & Stenke [102], AirClim employs emission data, together with information on altitude, latitude, and longitude, to assess the climate impacts of various flight routes. In addition to CO_2, AirClim considers water vapour, the impact of NO_X on ozone and methane, and the effects of CIC. The model integrates 3D aircraft emission information into its analysis and utilises previously determined atmospheric responses to calculate the temporal evolution of global near-surface temperature changes. The responses for H_2O- and NO_X-induced changes in ozone and methane are based on 85 steady-state simulations for the year 2000 via the DLR climate-chemistry model E39/CA [240]. Regarding the climate impact of CIC, atmospheric and climate responses, incorporating the local probability of satisfying the Schmidt-Appleman criterion and ice supersaturated regions, are obtained from simulations conducted with ECHAM4-CCMod by Burkhardt & Kärcher [241, 242].

The calculated climate impacts for each flight thus include both CO_2 and non-CO_2 effects. To enable combination with the LCA, the results were calculated with the metric GWP and integrated into the CC impact category. The GWP result for each flight is attached to the respective flight event during the LYFE simulation and interpreted after post-processing. Figure 4.4 shows the connection between LYFE, TCM, GRIDLAB, and AirClim, including input and output data. For a more detailed description of the links between the tools, please refer to Linke et al. [236].

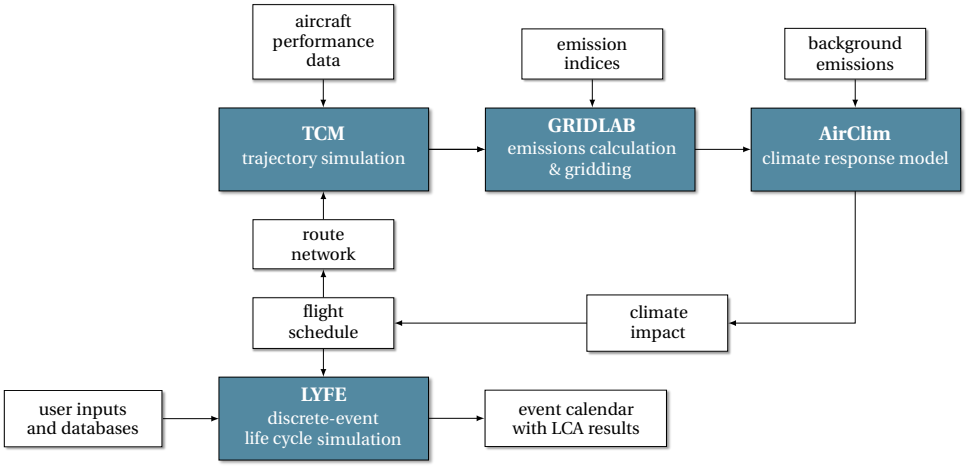


Figure 4.4: Schematic overview of the combined tools LYFE, TCM, GRIDLAB, and AirClim, including inputs and outputs.

4.4. Results

This section is divided according to the three individual scenario analyses. First, the overall life cycle impacts of the two aircraft configurations calculated with the discrete-event LCA are presented. Particular attention is given to the effects and potential of maintenance measures and their environmental impacts. This is followed by a detailed analysis of the flight operations, which includes the climate impacts and the environmental impacts of fuel production to compare the two energy carriers kerosene and PtL. In the third analysis, life cycle simulations in different flight networks illustrate the influence of adapted flight routes on the environmental impact. An overview of the results for all impact categories and scenarios can be found in the supplementary materials.

4.4.1. Comparison of Turbofan and Turboprop Aircraft

The entire life cycles of both aircraft designs were simulated in LYFE using discrete-event simulation based on the same flight plan (customised for the turbofan aircraft) and adjusted maintenance schedules. Table 4.2 provides an overview of the operational parameters of the turbofan and turboprop aircraft following the 25-year life cycle simulation.

The lower cruising speed of the turboprop aircraft (0.66 Mach) compared with that of the turbofan aircraft (0.78 Mach) results in a 5.1 % reduction in the number of FCs with increased flight time. Owing to the smaller number of flights, resulting in fewer kilometres travelled, the total ASK is approximately 5.7 % lower, given that both aircraft have the same number of seats (250 PAX).

Table 4.2: Operational parameters of the turbofan and turboprop aircraft over a lifetime of 25 years, including their relative deviations.

	Turbofan	**Turboprop**	**Delta**
Mach Number	0.78	0.66	-15.4 %
Total Distance	5.07×10^7 km	4.80×10^7 km	-5.7 %
Total FC	39,811	37,865	-5.1 %
Total FH	70,111	74,592	+6.0 %

The results for the impact category of CC with the indicator GWP are presented in Table 4.3. All results are expressed per aircraft lifetime and per ASK. The results of the climate impact evaluation during flight can be calculated only with the metric GWP.

Table 4.3: LCA results over all life cycle phases for the turbofan and turboprop aircraft with conventional kerosene over a lifetime of 25 years. The results are presented as totals over the entire life cycle and per ASK.

Life Cycle Phase	**Global Warming Potential** [tCO_2-eq./lifetime]		**Global Warming Potential** [gCO_2-eq./ASK]	
	Turbofan	**Turboprop**	**Turbofan**	**Turboprop**
Manufacturing	1,823	1,628	0.14	0.14
Fuel Production	143,894	106,291	11.35	8.86
Flights	1,099,550	880,085	86.70	73.37
Maintenance	1,669	2,186	0.13	0.18
End-of-Life	-522	-400	-0.04	-0.03
Total	1,246,414	989,791	98.28	82.52

The fuel production and climate impacts of flights represent the largest environmental shares in the life cycles of both aircraft, with flights accounting for approximately 88 % of the total impact. In almost all phases of the aircraft's life cycle, the turboprop has a lower environmental impact than the turbofan aircraft does (see Figure 4.5). The higher fuel efficiency of the turboprop engine results in fuel savings of 26.1 %. The environmental impact of aircraft manufacturing and end-of-life is significantly influenced by the OEWs of the aircraft. The turboprop is approximately 2.6 tonnes lighter than the turbofan-powered aircraft, resulting in lower environmental impacts during manufacturing and end-of-life, which can be attributed, among other factors, to the materials selected.

Maintenance is the only life cycle phase in which the turboprop has a higher GWP than the turbofan. Approximately 26.5 % of the maintenance-related environmental impacts are attributed to turboprop engine maintenance. This is due to the regular replacement

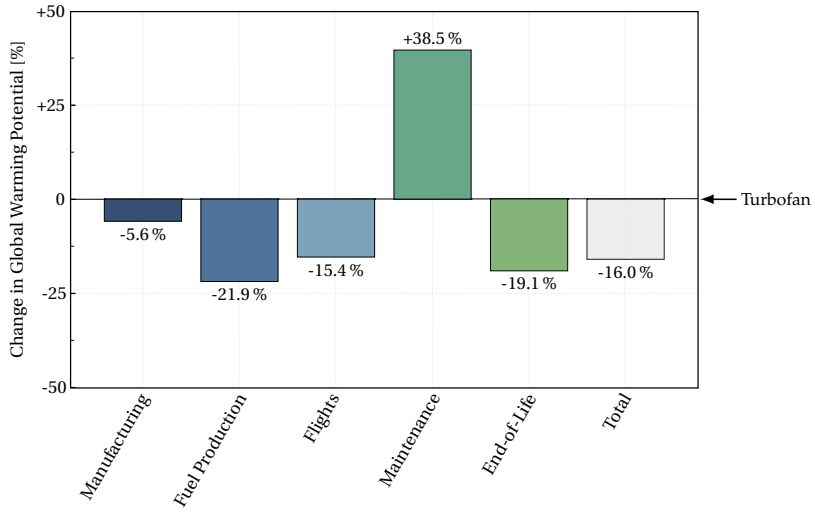


Figure 4.5: Changes in the GWP of the turboprop aircraft compared with that of the turbofan aircraft for each life cycle phase when powered with kerosene.

of the propeller, which typically must be replaced at approximately 10,500 FHs. In our simulation, the propeller is replaced seven times over the aircraft's lifetime, along with either a full overhaul or a hot section inspection. Figure 4.6 presents a direct comparison of the ecological implications of maintenance for the turbofan (top) and the turboprop (bottom) aircraft over their life cycles. The bar charts show the GWP results for the entire maintenance distributed across each year. The airframe maintenance (dark green) is almost identical for both aircraft. The peaks in the maintenance of the airframe, for example, in years 7, 12, 18, and 24, are due to extensive maintenance work, such as D-checks, during which, in addition to conducting a thorough inspection, the interior of the cabin is replaced and the aircraft is repainted [172]. The variations between the turbofan and turboprop engines can be seen in the engine maintenance bars (light green). The total accumulated GWP value of maintenance is depicted in both figures, emphasising the non-proportional distribution of maintenance over the aircraft's lifespan and the greater increases in certain years compared with others.

Given that there are no turboprop engines of this size in the civil sector, engine overhaul and propeller replacement are particularly subject to high uncertainties. With respect to propeller replacement, it was assumed that the entire propeller needs to be replaced, with no consideration of recycling opportunities. However, it can be assumed that improved material properties or repair technologies will be available by the time the aircraft enters service, which would result in reduced impact. If the propeller were to be replaced only during every second or third engine overhaul, the impact of maintenance could be reduced by an additional 13.1 % to 16.4 % (see Table 4.4).

Although the environmental impact of turboprop aircraft maintenance is considerably greater than that of turbofan aircraft maintenance, the relative influence of maintenance over the aircraft's life cycle remains low. For turbofan aircraft, this value is approximately

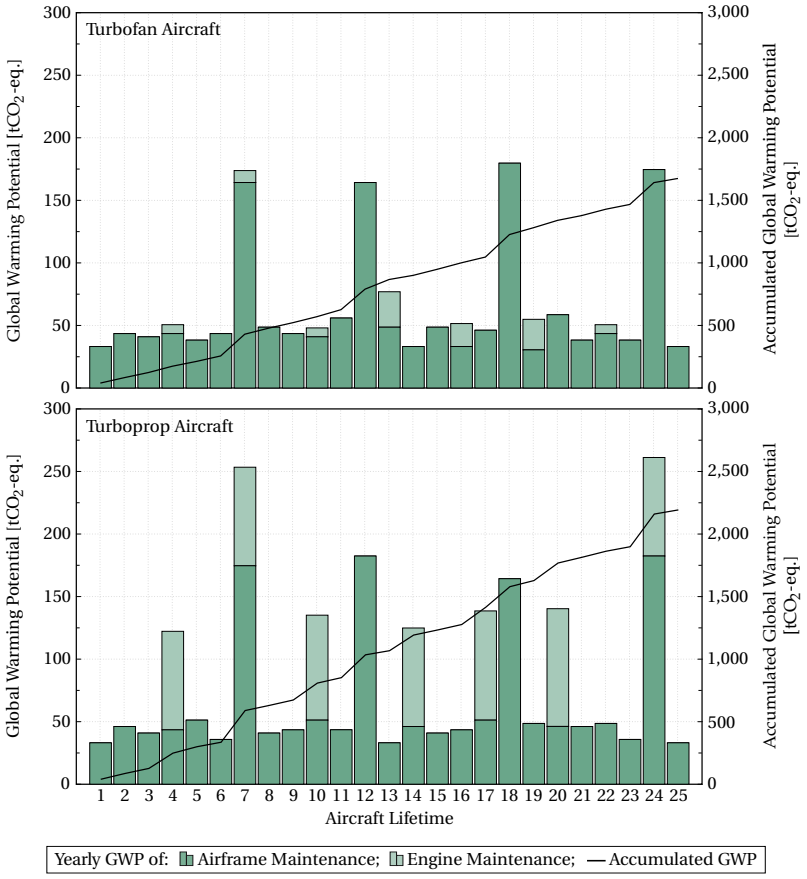


Figure 4.6: Yearly distribution of the GWP of the airframe and engine maintenance (primary axis) and the accumulative GWP of total maintenance over the turbofan (top) and turboprop (bottom) aircraft lifetimes (secondary axis).

Table 4.4: Reduction in GWP for different propeller replacement intervals during engine overhauls.

Propeller Replacement Interval	**Global Warming Potential** [$kgCO_2$-eq.]	[%]
Every Engine Overhaul	2,186,149	0.0
Every Second Engine Overhaul	1,899,473	-13.1
Every Third Engine Overhaul	1,827,804	-16.4

0.13 %, whereas for turboprop aircraft, it is 0.22 %. Nevertheless, maintenance and overhaul practices can indirectly reduce the environmental impacts of flight operations by maintaining or improving aircraft fuel efficiency, for example through regular engine washing [109]. This highlights that the overall environmental relevance of maintenance extends beyond its direct impacts alone.

4.4.2. Comparison of Kerosene and Power-to-Liquid

The selection of the energy carrier has a decisive influence on the overall environmental impacts of the two aircraft designs. However, the complexity and differences between the two fuel types and propulsion technologies become apparent only when the results are examined at flight-level. The environmental assessment at flight-level can be performed for individual routes, considering the velocities, distance flown, altitude, longitude, and latitude. To facilitate interpretation of the results, the climate impacts of the flights and the environmental impacts of fuel production are summarised and classified into the categories of very short-haul (up to 800 km), short-haul (800-1,500 km), and medium-haul (1,500-4,000 km) flights in accordance with the aircraft transportation datasets in ecoinvent [243]. Figure 4.7 illustrates the distribution of the climate impacts, expressed as GWP per ASK, for the flight operations and fuel production phases for kerosene (left) and PtL (right). The left side of the violin plots (dark blue) represents the values for the turbofan, and the right side (light blue) represents those for the turboprop aircraft. The shape of the violins indicates the density distribution of all individually calculated flight impacts. In addition, the median of the data points and the 25th and 75th percentiles (1st and 3rd quartiles) are provided. A long violin plot indicates that the data points are distributed over a wide range with a few outliers.

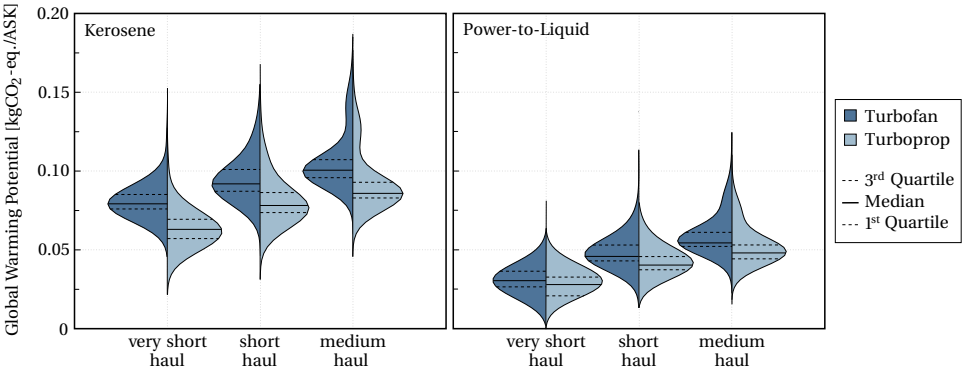


Figure 4.7: Distribution of the GWP results for the flight distance categories of very short-haul (up to 800 km), short-haul (800-1,500 km), and medium-haul (1,500-4,000 km) flights for kerosene (left) and PtL (right), including a comparison between turbofan and turboprop aircraft. The median and quartiles are shown in the violin plots to indicate the spread of the data.

PtL has only approximately half the impact of kerosene in terms of CO_2-eq. The production of PtL has a smaller impact on CC (and almost all other impact categories) due to renewable energy production. Furthermore, PtL has positive effects when combusted because of its reduced CO_2 and particulate emissions. A comprehensive examination of the production and combustion of kerosene and PtL can be found in Papantoni et al. [116]. Furthermore, the median values for the turboprop aircraft are lower than those for the turbofan aircraft in all three distance categories. This is mainly due to the higher fuel efficiency of the turboprop engine. The lower cruising altitude and reduced fuel consumption of the turboprop aircraft are particularly beneficial in terms of non-CO_2 effects.

The study revealed a positive correlation between flight distance and GWP per ASK. In contrast to the aircraft transportation datasets in ecoinvent and similar studies that link longer flight distances to lower GWP values, we included the exact locations and altitudes of the aircraft in each flight. The altitude, which typically increases with increasing flight distance, leads to an increase in non-CO_2 effects (NO_X, H_2O, and CIC). Despite the specific emissions of NO_X and CO_2, which are typically lower for shorter flights, this leads to an increase in the overall climate impact for longer flight segments. For a more detailed explanation, please refer to Dahlmann et al. [170].

4.4.3. Comparison of Flight Schedules

To incorporate the different operational characteristics of the two aircraft, a second flight schedule is introduced specifically for the turboprop aircraft. Figure 4.8 shows that the turboprop aircraft is more efficient when operated within its dedicated turboprop network with shorter flights and an increase in the number of performed FCs by almost 21.4 % to a total of 45,972 FCs. By utilising the turboprop aircraft on an adapted flight schedule, 6.7 % of the fuel can be saved, while maintaining the same transport performance. Nevertheless, after 25 years, the absolute number of performed ASKs for the turboprop aircraft (both in the turbofan and the turboprop network) is considerably below the transport capacity of the reference turbofan aircraft. A theoretical conversion from a turbofan to a turboprop aircraft fleet would require operating 5.4 % more aircraft to achieve the same transport capacity. If an adapted turboprop network is used, this number increases to 39.1 % more aircraft. The impact of producing or maintaining these additional aircraft would have to be considered in a fleet-wide analysis.

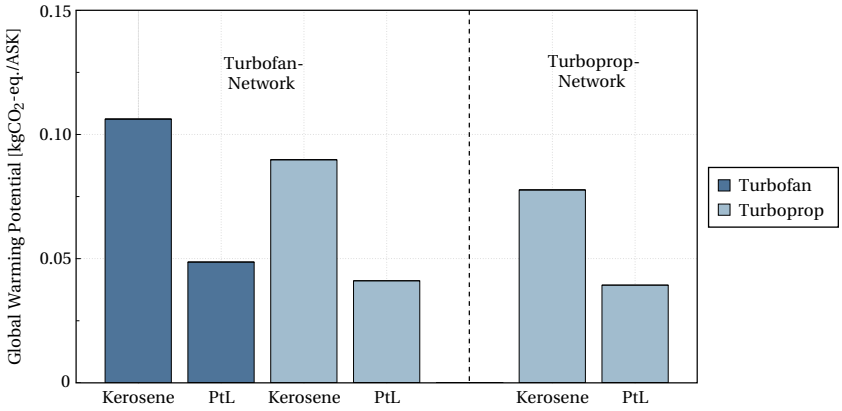


Figure 4.8: Comparison of the GWP per ASK for turbofan and turboprop aircraft, assuming a flight network adapted specifically for the turboprop. All the results are given for both kerosene and PtL.

4.5. Discussion

The combination of discrete-event LCA with climate impact evaluation enables detailed scenario analyses of the overall life cycle, especially for flight operations and maintenance. A comparison of the two aircraft types indicates that the use of turboprop aircraft can reduce the impact on the CC category by a total of 16.0 %. The higher efficiency of the turboprop engine and the lower flight altitude are the main reasons for this. In accordance with other published works (e.g., Graham et al. [180]), the expansion of turboprop aircraft usage should be encouraged. However, converting to turboprop aircraft within a global fleet would result in a reduction in the overall transport performance due to the lower cruising speed, which would necessitate the use of more aircraft to achieve the same transport capacity. In this study, the LCA was conducted exclusively at the aircraft-level and does not account for the additional aircraft required to maintain an equivalent transport capacity. A fleet-level analysis may yield different conclusions.

Another notable aspect of the LCA is the evaluation of maintenance activities. The results indicate that the GWP of maintenance activities for the turboprop aircraft increases significantly (by approximately 38.5 %) in comparison to that of the turbofan aircraft. The primary factor in this increase is the regular replacement of the propeller, which is based on the maintenance parameters of significantly smaller commercial aircraft. As no turboprop engine of this size currently exists in the commercial aviation sector, the relevant maintenance conditions are highly uncertain. Furthermore, the recycling potential of LLPs was neglected, which could have a significant impact, especially with respect to propellers made of composite materials. The discrete-event simulation enables deeper insight into aircraft maintenance processes and thus provides an ideal basis for analysing new maintenance activities and their environmental impacts.

In line with the results of previous studies, our investigations demonstrate the significant influence of the operating phase on the overall environmental impact. The share of the flight phase in the overall result is approximately 90 %, regardless of whether kerosene or PtL is used. The production of the energy carriers accounts for almost all of the remaining overall life cycle impacts. The use of PtL offers a reduction potential of 45.6 %, which is due primarily to the combination of more efficient engine combustion, CO_2 from renewable energy sources, and fewer particulates. In particular, the reduction in the warming effect of CIC is an advantage here. These findings align with prior research, such as Batteiger et al. [244], which also highlights the ecological benefits of PtL over conventional kerosene fuels. Moreover, the results of our study contradict the correlation observed in [18, 29, 245], where flights are assessed solely via emission inventories, and demonstrate that the climate impact per flown kilometre increases with increasing flight distance. This is mainly due to the cruising altitude, which is usually higher for long distances and introduces further non-CO_2 effects. By taking these two aspects into account, we calculated the climate impact on a more detailed basis than in conventional LCA studies.

While the findings of this study provide valuable insights, several limitations must be acknowledged. First, it is important to note that our calculations require a significant amount of aircraft-specific performance data and many operational inputs, which limits the ability to transfer the results to other aircraft types. Owing to data availability

issues, historical datasets often had to be used to generate the LCI, which may limit the applicability of our findings to future scenarios. A prospective dataset could increase the robustness and relevance of the conclusions. Second, our LCI is partly based on assumptions, e.g., regarding the material composition of the engines or geographical restrictions. This has an impact, for example, on the LCA of maintenance activities, which are significantly greater for turboprop aircraft because of the regular replacement of propellers. These assumptions, although they are based on the best available estimates, introduce a degree of uncertainty that should be considered in future research. The results of the climate impact assessment may vary significantly under different boundary conditions and assumptions as the flown network and flight trajectories are crucial due to the existing background emissions. The upscaling of the turboprop engine introduces additional uncertainties with respect to the calculated fuel efficiency and climate impact. Taking these limitations into account could further strengthen the validity and applicability of the study results.

4.6. Summary and Outlook

The main objective of this study was to assess the environmental impacts of two distinct aircraft designs, each equipped with a different propulsion system: a turbofan engine and a turboprop engine. The study focused on the environmental evaluation of the two aircraft, with a particular emphasis on in-flight climate impacts, fuel type, flight scheduling, and maintenance. To achieve this, we coupled a discrete-event LCA and a climate response model to simulate and analyse the aircraft's life cycles. Given that flight operations is the most influential phase for the CC impact category, the savings potential, particularly through the use of PtL and adjustments to the flight network, is most evident in this phase. Furthermore, by incorporating the flight altitude and non-CO_2 effects, it was demonstrated that these factors have a significant impact on the climate. In contrast to the findings of other LCA studies, the climate impact per kilometre flown increases with increasing flight distance.

Despite the better environmental flight performance of the turboprop aircraft, it has greater maintenance-related impacts. However, maintenance is a crucial element in reducing emissions. According to Jakovljević et al. [246], degradation behaviour can be improved through proper and timely aircraft maintenance, which in turn increases the efficiency of the engine. In particular, the lower environmental impact of maintenance in relation to flight operations makes maintenance a beneficial and attractive lever for reducing the overall environmental impact, and, at the same time, enables the use of new technologies and concepts.

Our discrete-event LCA methodology enables the evaluation of smaller changes in aircraft design, such as those resulting from a new propulsion system and its maintenance. The analysis of minor modifications to the life cycle facilitates the assessment of their environmental impact. Future research should build on the findings of this study to deepen the understanding of the relationship between conventional LCA and climate impacts in aviation and to alter existing assumptions. For example, the use of prospective datasets that take into account expected technological advances would provide a more future-oriented perspective on environmental impacts. An expansion of the geographical

scope could further improve the global applicability of the results. To gain a more realistic assessment, it is also essential to examine the end-of-life phase in greater detail, particularly in relation to LLPs, which are replaced more frequently during some maintenance events. By considering innovative recycling scenarios, new technologies can become even more attractive. Furthermore, future studies could focus on reducing uncertainties in LCIs by incorporating more detailed and material-specific data, including probability distributions. Finally, the integration of dynamic modelling approaches could provide additional insights for assessing future technologies. Taking these aspects into account would contribute to a more comprehensive understanding and pave the way for more effective mitigation strategies.

Part II –

Application to New Aircraft Technologies

Chapter 5

Why Maintenance Matters in Environmental Life Cycle Assessment of Hydrogen-Powered Aircraft

Minimising the environmental impact of aviation requires the development of new technologies. Hydrogen is being explored as a promising alternative energy carrier, yet its use requires major design changes, including cryogenic tanks, new fuel distribution systems, and the integration of a fuel cell system. While these technologies can reduce in-flight emissions, little is known about their environmental implications for maintenance. In this study, we perform a discrete-event life cycle assessment of a hydrogen-powered mild hybrid-electric aircraft for short- to medium-range operations, focusing on the environmental implications of new maintenance activities. Compared to a conventional kerosene-powered reference aircraft, the hydrogen concept can reduce overall life cycle impacts by more than 75 %, primarily through the elimination of direct CO_2 emissions during flight. However, maintenance-related environmental impacts increase by up to 45 %, mainly driven by hydrogen tank servicing and fuel cell replacement. An uncertainty analysis reveals significant data gaps, particularly regarding component lifetimes, with potential impacts being substantially higher than deterministic estimates suggest. These findings provide methodological guidance for future life cycle assessments of hydrogen-powered aircraft and highlight critical data needs for industry stakeholders and policymakers.

This chapter has been submitted as:
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5.1. Introduction

Hydrogen-powered aircraft are regarded as a promising pathway towards more sustainable aviation due to their potential to significantly reduce life cycle GHG emissions compared with conventional kerosene. Several European programmes promote research and development of hydrogen aviation technologies [247, 248] and initial prototypes have already been successfully tested in projects such as the Hydrogen Aviation Lab [249] or initiatives from Zeroavia [250]. While hydrogen combustion eliminates CO_2 emissions during flight, NO_X emissions and water vapour are still emitted, and their climate effects depend strongly on engine concept and atmospheric conditions [251].

Beyond emissions, the adoption of hydrogen requires major design changes that introduce challenges regarding infrastructure, safety, and regulatory compliance [12, 252–254]. These design changes also alter the operational characteristics of the aircraft in ways that extend well beyond the flight phase and affect the entire aircraft life cycle. Changes in component lifetimes, increased maintenance requirements, and longer downtimes can further reduce aircraft utilisation and trigger cascading effects on life cycle environmental impacts. Yet, such interdependencies are rarely captured in existing LCAs, which usually assume fixed operating parameters [141, 255]. While this simplification is acceptable for conventional aircraft, it is limiting for hydrogen-powered aircraft concepts. In particular, component degradation, maintenance schedules, and operational availability are subject to greater uncertainties, which static approaches are unable to adequately capture.

To address this gap, we present the first application of a discrete-event LCA to a hydrogen-powered aircraft concept, that models maintenance as a dynamic, event-driven process within the aircraft life cycle. Given the prospective character of the analysis and the substantial knowledge gaps in inventory data for technologies that have not yet reached commercial maturity, we further integrate uncertainty modelling to capture potential variations in component manufacturing, lifetime, and maintenance requirements. This dynamic framework explicitly accounts for interdependencies between downtime, maintenance frequency, and component lifetimes. Unlike conventional static LCAs, it enables a temporally resolved assessment of environmental impacts over the full aircraft lifetime. We apply this approach to a hydrogen-powered hybrid-electric aircraft integrating a fuel cell system, cryogenic hydrogen storage, and a redesigned propulsion system for direct hydrogen combustion. Given the prospective character of the analysis and the limited availability of reliable datasets, we further integrate uncertainty modelling. This captures potential variations in critical aspects such as component manufacturing, lifetime, and maintenance requirements. The results provide methodological guidance for LCAs of hydrogen-powered aircraft and identify critical data gaps that are relevant for industry stakeholders and policymakers to assess the long-term environmental performance of emerging technologies in aviation.

This chapter is structured as follows: Section 5.2 discusses the fundamentals and life cycle impacts of technologies used in hydrogen-powered aircraft. Section 5.3 explains the discrete-event LCA, including the creation of LCIs and the integration of uncertainties. The results are presented and discussed in Section 5.4. The chapter ends with a discussion (Section 5.5) and outlook on future studies (Section 5.6).

5.2. Hydrogen in Aviation

This section provides the technological background for hydrogen-powered aviation. It introduces the key aircraft technologies considered in this study and reviews the current state of LCA research on hydrogen-powered aircraft.

5.2.1. Hydrogen-Powered Aircraft Technologies

In recent years, a variety of new aircraft concepts have emerged that aim to reduce the environmental impact of aviation and improve its efficiency. All-electric aircraft concepts are limited by the low energy density of today's batteries and significant weight penalties [256, 257]. Therefore, alternative energy carriers are gaining attention, especially for long-range operations [258]. Hydrogen eliminates CO_2 emissions during flight, which represents a key advantage over conventional jet fuels [259]. Still, the overall climate impact remains uncertain, as NO_X emissions and contrail formation at cruise altitudes can contribute significantly to non-CO_2 effects, though the magnitude of these effects varies considerably [260–263]. These effects may substantially offset the expected environmental benefits.

The implementation of hydrogen-based technologies in aviation is associated with significant challenges, particularly regarding fuel storage, system integration, safety, and material durability [264]. The adoption of hydrogen as an aviation fuel should always be accompanied by sustainable production pathways and requires substantial modifications to aircraft systems with direct implications for maintenance requirements [12]. These include redesigning fuel tanks, aircraft engines, and possibly implementing novel subsystems specific to these technologies [262, 265]. Especially in hybrid-electric configurations, this also involves integrating new key technologies for energy conversion such as fuel cell systems. The following sections examine hydrogen storage, propulsion, and fuel cell systems in more detail, with particular attention to their maintenance implications.

5.2.1.1. Hydrogen Storage

While conventional jet fuel can be stored in the aircraft's wings, hydrogen requires special conditions for safe and efficient storage, posing significant challenges for the development of suitable tank technologies [266]. Due to the low volumetric energy densities, gaseous hydrogen requires substantially more storage space for the same amount of energy as conventional jet fuel [267]. Maximum volumetric energy density is achieved under cryogenic conditions at 20 K and 1–4 bar, at which point hydrogen exists in liquid form [268]. Liquid hydrogen cryogenic storage is therefore the preferred approach for aviation applications [266]. Current research focuses on type V tanks consisting of CFRP, which offer the best structural integrity and weight-saving potential [269]. Despite this progress, maintenance requirements for cryogenic tank systems remain largely uncharacterised [270]. A thorough understanding of inspection intervals, component lifetimes, and servicing procedures will therefore be essential for both airworthiness certification and the assessment of life cycle impacts.

5.2.1.2. Fuel Cell System

In hybrid-electric configurations, hydrogen can additionally power fuel cell systems by converting chemical energy directly into electrical power. These systems consist of a cell stack and a balance-of-plant comprising air compressors, humidifiers, heat exchangers, and cooling pumps [271]. In aviation, especially Proton Exchange Membrane (PEM) fuel cells are currently being tested for various applications, in particular as an alternative energy source for power supply or as an APU in all- or more-electric aircraft [272]. They provide power with lower environmental impacts and can produce useful by-products such as water or oxygen-depleted air to inert fuel tanks [273]. However, the stack is subject to progressive degradation mechanisms, including membrane deterioration, catalyst ageing, and mechanical stress from thermal and pressure cycling. This requires regular replacement over the aircraft's service life and extensive maintenance to meet aviation safety and durability requirements [273].

5.2.1.3. Hydrogen-Powered Propulsion System

Hydrogen combustion engines require substantial modifications to conventional turbojet architecture, including adapted materials and advanced cooling techniques [274, 275]. When being stored cryogenically, hydrogen must be fully vaporised into gaseous form before being injected into the engine [276]. The fuel distribution system therefore requires an engine-mounted vaporisation system comprising pumps, advanced valves, and heat exchangers [277]. In particular, the design and position of heat exchangers remain a widely discussed topic in the literature [275, 278], with direct consequences for system accessibility and maintainability. These additional subsystems increase overall system complexity and introduce new thermal loads that may accelerate material degradation [279], reduce engine lifetime compared to conventional systems [1, 274], and increase maintenance requirements to meet aviation safety standards [12].

5.2.2. Life Cycle Assessment Studies of Hydrogen-Powered Aircraft

Numerous studies have examined the fuel life cycle (well-to-wake) of LH_2 [13, 30, 63, 280]. They show that LH_2 can offer significant environmental benefits with CO_2 reduction potentials of 50 % or more compared to conventional kerosene, depending on aircraft type, flight mission, and production pathway [64]. In addition, benefits can arise in areas such as ozone depletion, abiotic depletion, and human toxicity [1]. The environmental impact of hydrogen production depends largely on the energy source used for the electrolysis [281, 282]. Beyond hydrogen production, a comprehensive LCA must also account for technical and infrastructural challenges [1]. These include, for example, the availability of hydrogen at airports [283] and increased maintenance requirements arising from novel components and strict safety criteria [12, 284].

Some LCA studies focus on the environmental impacts of specific hydrogen-related technologies, such as the production and integration of hydrogen tanks [285] or PEM fuel cell systems [286]. Lightweight hydrogen storage tanks can be one of the main drivers to reduce the environmental impact - in particular through the efficient use of materials and

energy [287]. For fuel cell systems, the impact category of MM and ECF for production lead to high environmental impacts [286, 288, 289].

LCA studies that take a complete life cycle perspective of emerging technologies in aviation into account are still rare [290]. This is usually owing to non-existent or insufficient datasets [18, 25] as well as the high complexity of novel aircraft concepts, which are difficult to map entirely [291, 292]. Thonemann et al. [293] highlight that in the ecological assessment of hybrid-electric aircraft concepts, burden-shifting is a central problem - especially if impact categories related to resource consumption or toxicity are not sufficiently taken into account. Such shifting effects can only be adequately captured by a thorough LCA over the entire aircraft life cycle. Yet, many of the underlying hydrogen technologies remain at an early development stage and exist only as design concepts. Reliable information on production, service life, maintenance requirements, and performance under real conditions remain limited. In addition, future developments of hydrogen supply and infrastructure remain difficult to predict. Therefore, the awareness of uncertainties is essential when considering prospective concepts [209, 290]. This represents a central methodological focus of the present work.

5.3. Method

This section describes the methodological framework of the study. It outlines the goal and scope definition, the LCI modelling, and the integration of maintenance-related uncertainties into the LCA approach.

5.3.1. Goal and Scope Definition

The aim of this study is to evaluate the environmental life cycle impacts of a hydrogen-powered aircraft, with particular emphasis on maintenance-related burdens and their associated uncertainties. We consider two short-range aircraft designs from DLR's EXACT project. The baseline kerosene-powered aircraft is based on an Airbus A321neo with a capacity of 250 PAX and an OEW of 44.9 t. This conventional turbofan aircraft, as described by Atanasov et al. [225], has previously been examined from an environmental perspective in Rahn et al. [291] and serves as a reference for comparison with the novel hydrogen aircraft concepts.

The alternative concept is a hydrogen-powered MHEP aircraft concept derived from the baseline configuration, with similar aerodynamic and structural characteristics [294]. In this architecture, the gas turbine provides all propulsive power, while the fuel cell system is used exclusively as an APU to supply the aircraft's electrical loads. Hydrogen is used to fuel the gas turbine for primary propulsion and to supply the fuel cell system. The MHEP aircraft has an OEW of 52.7 t and a projected entry-into-service in 2040. The aircraft design relies on hydrogen as its main energy source. Significant modifications affect the fuel storage, distribution, and energy supply systems, including:

- two cryogenic CFRP-tanks;
- a fuel cell system;
- a hydrogen propulsion and distribution system.

Figure 5.1 presents the MHEP concept, highlighting the hydrogen tanks, fuel cell system, and the modifications made to the engines.

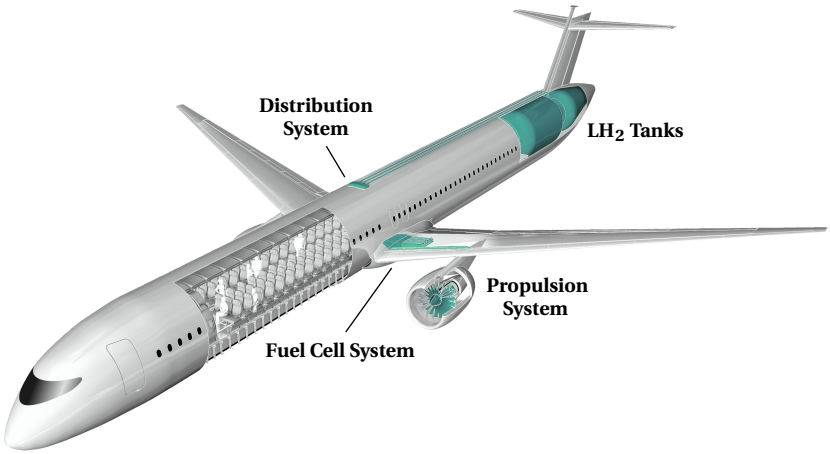


Figure 5.1: MHEP aircraft concept from the EXACT project. The two LH_2 tanks, the fuel cell system, and the advanced propulsion and distribution system are highlighted in green (source: DLR, internal documentation).

A cradle-to-grave LCA was performed, covering all life cycle phases of the aircraft, from production to the end-of-life. Production and maintenance activities are assumed to take place in Germany and the aircraft are operated within Europe. Two functional units are considered: per aircraft lifetime and per ASK. The latter allows comparison independent of the load factor. A service life of 25 years was assumed. For the LCA calculation, the LCIA method EF 3.1 [295] was chosen for its reliability in quantifying environmental performance.

5.3.1.1. Liquid Hydrogen Storage

The two LH_2 tanks are arranged in a tandem configuration behind the rear bulkhead. The front tank has a cylindrical shape, while the rear tank is conical to optimise integration within the fuselage geometry. The type V tanks consist of two CFRP shells with insulation layers. Together, the two tanks provide a total internal volume of 59.7 m^3.

5.3.1.2. Fuel Cell System

The PEM fuel cell system replaces the APU and provides electrical energy on ground, supplies emergency power during flight, and supports engine start-up. It is composed of four units with nine stacks each, resulting in an energy output of 1356.2 kWh.

5.3.1.3. Propulsion and Distribution System

The fuel propulsion and distribution system is specially designed for cryogenic hydrogen. Vacuum-insulated tubes minimise heat loss and prevent premature evaporation, while pressure-controlled valves and redundant safety systems ensure a controlled fuel supply and prevent leakage. The vaporisation system is a key component of the propulsion system. It converts LH_2 into gaseous hydrogen via a heat exchanger and ensures suitable temperature and pressure conditions for combustion. Further details on the system layout and key functional principles can be found in Meissner et al. [12].

5.3.2. Generation of the Inventory

We used the ecoinvent database version 3.9.1 with the cut-off by classification system model [146]. Details on all inventories with their underlying assumptions for both conventional and novel MHEP aircraft concepts are provided in the supplementary material.

5.3.2.1. Manufacturing

The LCI of the baseline aircraft concept is based on Rahn et al. [291] and was adapted for the MHEP aircraft. While the material breakdown remains largely unchanged, we made adjustments to the mass distribution to align with the MHEP concept. The most significant design changes are related to the systems, for instance, owing to the elimination of the APU (being substituted by the fuel cell) and the adaptation of the engine for hydrogen. The inventories of the additional components were modelled in detail and incorporated into the overall aircraft design.

The inventory of the cryogenic hydrogen tanks was generated using detailed information on the manufacturing processes for CFRP laminates. The primary and secondary foreground data was collected during the manufacturing of a half-tank demonstrator at DLR using automated fibre placement. Primary data include direct measurements of material and energy consumption, as well as information on waste generation. Secondary data, such as material properties for the insulation layers, were obtained from literature [296–298] and from the corresponding background database. All collected data were subsequently scaled to represent the two tanks in the aircraft.

The inventory of the PEM fuel cell system was created using data from DLR's Airfox tool for dimensioning and simulating fuel cell systems for aviation applications based on experimental data from stack tests carried out in the laboratory [299]. The collected data include the dimensions of the fuel cell stack, the thickness of its components, the weight of the balance-of-plant units, and the number of cells, stacks, and systems. The methodology for calculating the weight and material composition of the fuel cell stack components was adopted from Evon et al. [286]. While the original study focused on a 70-seat regional aircraft concept, the methodological approach was applied and modified for the current MHEP aircraft with 250 PAX. To represent the technological state anticipated for 2040, the inventory was additionally sized on the basis of a projected power density of 4–5.6 kW/kg, as reported by Thonemann et al. [293].

5.3.2.2. Flights and Fuel Production

To assess the environmental impact of flight operations, both CO_2 and non-CO_2 effects need to be considered. Empirical data on contrail formation for hydrogen-powered aircraft are limited, and the associated impacts are subject to considerable uncertainties [300]. In this study, the climate impact of flights is quantified using the methodological approach presented in Rahn et al. [291]. For the hydrogen-powered MHEP aircraft, project-specific emission data are used, while corresponding data for the reference aircraft are adopted from Rahn et al. [291]. As flight operations are not the primary focus of this study, the underlying emission modelling is not further refined. For comparability, the same flight network is applied to both aircraft concepts based on Kühlen et al. [229]. Details on the underlying tools, calculations, and assumptions are provided in Kühlen et al. [193], Linke et al. [236], and Dahlmann et al. [170].

The fuel production inventories are based on the ecoinvent datasets *market for kerosene* and *market for hydrogen, liquid*, representing the European market. Using background inventories from the same database ensures methodological consistency and comparable system boundaries for both fuel types. The applied hydrogen dataset represents the default European market inventory provided by ecoinvent. Although the environmental impacts of hydrogen production depend strongly on the production pathway and electricity supply [282], assessing alternative hydrogen production scenarios is beyond the scope of this study, which focuses on maintenance-related life cycle impacts.

5.3.2.3. Maintenance

The inventories of the maintenance activities were created using the approach presented in Rahn et al. [172]. These include, for example, the energy required to operate the hangar or the use of special maintenance equipment or auxiliary goods. In particular, the replacement of certain components represents a critical contribution to overall maintenance [226] (see Table 5.1). Depending on the component, replacement may be required after a predetermined lifetime, as in the case of LLPs, or initiated based on observed

Table 5.1: Maintenance activities for hydrogen technologies in the MHEP aircraft, including their durations and intervals. Data are compiled from literature [12, 255, 284].

Hydrogen System	Check	Type	Duration	Interval
LH_2 Storage	Leakage Test	Inspection	20 h	440 FH
	LH_2 Tank	Replacement	324 h	22,800 FH
	Tank Structure	Inspection	4 h	4,000 FH / 2,000 FC
	Valves	Inspection	17 h	2,500 FH / 3,000 FC
Fuel Cell System	Filters and Sensors	Inspection	12 h	8,500 FH
	Fuel Cell Cooling System	Inspection	4 h	3,000 FH
	Fuel Cell Stack	Replacement	48 h	10,000 FH
Hydrogen Propulsion System	High-Pressure Pump	Inspection	4 h	6,000 FH
	LH_2 Distribution System	Inspection	23 h	2,500 FH / 2,500 FC
	Vaporisation System	Replacement	6 h	15,000 FH

failure rates. As no historical maintenance data is available for the novel components, the corresponding maintenance tasks were estimated using analytical approaches. The maintenance schedule was adapted from studies that applied comparable estimation approaches for the same or similar technologies [12, 255, 284]. In particular, the MHEP concept involves changes in regard to the LH_2 storage, the fuel cell system, and the engine and distribution system. Table 5.1 provides an overview of the new MHEP maintenance checks, including their durations and intervals. When two intervals are specified, the check is performed according to the 'whichever occurs first' principle. The supplementary material provides a more detailed breakdown of the methodology employed for creating the maintenance tasks as well as the content of each task.

5.3.2.4. End-of-Life

We modelled the end-of-life phase using an inventory of energy and material values based on the credit for avoided virgin production method [112]. This method accounts for the energy savings achieved through recycling and reuse compared to the production of virgin materials and recovered energy through incineration.

5.3.3. Discrete-Event Life Cycle Assessment with Uncertainty Modelling

The operational phase of aircraft consists of flights and maintenance events and typically accounts for up to 99.8 % of the total life cycle impacts [35, 301]. However, conventional LCAs often rely heavily on assumptions and average values to represent this life cycle phase. Especially for new aircraft concepts, these assumptions can be inaccurate. For this reason, we perform a discrete-event LCA using the Life Cycle Analysis Framework for Environment & Economics (LYFE^2) developed by DLR.[7] LYFE^2 is a Python-based, modular framework that models a series of individual events via state variables that change at discrete points in time [302]. At its core, LYFE^2 creates an event calendar that covers all events that occur during the aircraft's lifetime, including its production, each individual flight and maintenance event as well as end-of-life. For each event in the calendar, the corresponding LCI is retrieved and evaluated individually; the results are then accumulated across all events to obtain the total life cycle impacts. At the end of the simulation, it comprises roughly 85,000 events. For better comparability, both life cycle simulations are based on the same flight schedule.

While discrete-event LCA increases the level of detail compared to conventional LCA, more knowledge does not necessarily reduce uncertainty; on the contrary, pursuing more detailed knowledge can even amplify it [26]. In recent years, interest in uncertainty within LCA studies has increased [303] and its treatment remains one of the "fundamental challenges affecting LCA reliability" [304]. Therefore, this study places particular emphasis on uncertainty quantification. Especially the maintenance of new technologies is affected by a high degree of epistemic uncertainty resulting from a lack of knowledge surrounding the technologies themselves, their degradation, and maintenance scope.

[7] The framework was published under the name LYFE in previous work. Following its further development, it has been renamed to LYFE^2 to reflect its extended functionality.

To quantify the propagation of uncertainty in maintenance activities, we followed a two-step approach (see Figure 5.2). In the first step, Monte Carlo simulations were applied to the cradle-to-gate LCAs of individual maintenance tasks related to new technologies. We model this uncertainty using the Pedigree approach [237]. The Pedigree approach translates expert judgement into probability distributions based on experimental data. This allowed us to capture the uncertainty associated with the environmental impacts of maintenance activities at the task-level. In the second step, operational parameters, such as task intervals and durations, were implemented. For immature technologies, precise point estimates are often of limited informative value; instead, approaches using best- and worst-case scenarios are more appropriate for representing uncertainty [258]. To do so, the distribution results from the Monte Carlo simulations of the individual LCAs were imported into LYFE^2, where they were combined to assess the overall maintenance-related environmental impacts. This approach provides a structured way to incorporate both parametric uncertainty at the task-level and operational variability.

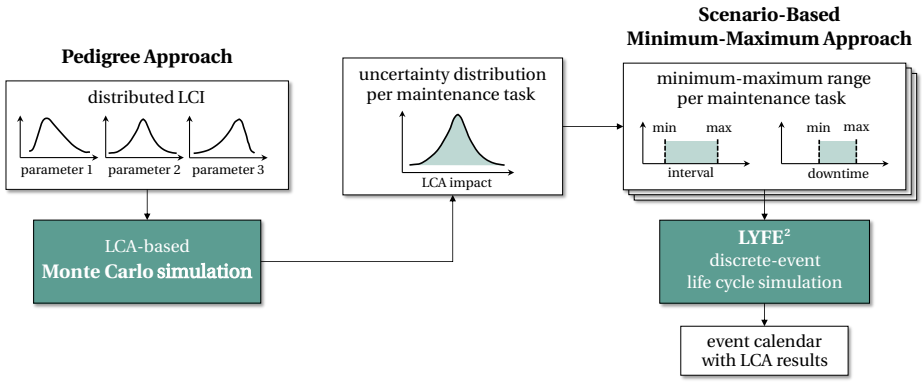


Figure 5.2: Schematic representation of uncertainty propagation: Task-level uncertainties are modelled using a Pedigree approach for each individual LCA, and operational uncertainties are captured via a scenario-based minimum–maximum approach for integration into LYFE^2.

Overall, we consider 177 parameters as uncertain, including 26 for the fuel cell system, 108 for the hydrogen storage, and four for the vaporisation system. Additionally, there are 39 uncertain input parameters for the maintenance schedule. Fuel cell and vaporisation system-related uncertainties primarily concern the material used in their production and hydrogen storage uncertainties reflect scaling effects. Maintenance parameters include task-specific downtime and intervals, for which ranges were defined based on expert judgment and literature. Since operational parameters such as task intervals and durations represent independent physical quantities with no direct functional dependency, all uncertain parameters were assumed to be independent. Non-linear secondary effects, such as cascading maintenance delays, are implicitly captured through the discrete-event simulation. An overview of all uncertainty parameters can be found in the supplementary material.

5.4. Results

The following section presents the life cycle environmental impacts of both aircraft concepts, with particular focus on the maintenance phase and its associated uncertainties. First, we compare the deterministic LCA results of baseline and the hydrogen-powered MHEP aircraft over all life cycle stages. Subsequently, the maintenance phase is analysed in more detail, accounting for uncertainties stemming from limited knowledge in prospective assessments. A full overview of all results is provided in the supplementary material.

5.4.1. Overall Life Cycle Results

Within 25 years, the baseline aircraft performs approximately 40,100 FCs with a total of more than 70,200 FHs. The FCs represent typical short- to medium-haul operations within Europe. The MHEP aircraft performs around 68,000 FHs, which corresponds to a 3.2 % reduction relative to the baseline aircraft (see Table 5.2). This reduction is attributed to the additional maintenance activities and longer downtimes required for the hydrogen technologies. The LCA results are given per ASK.

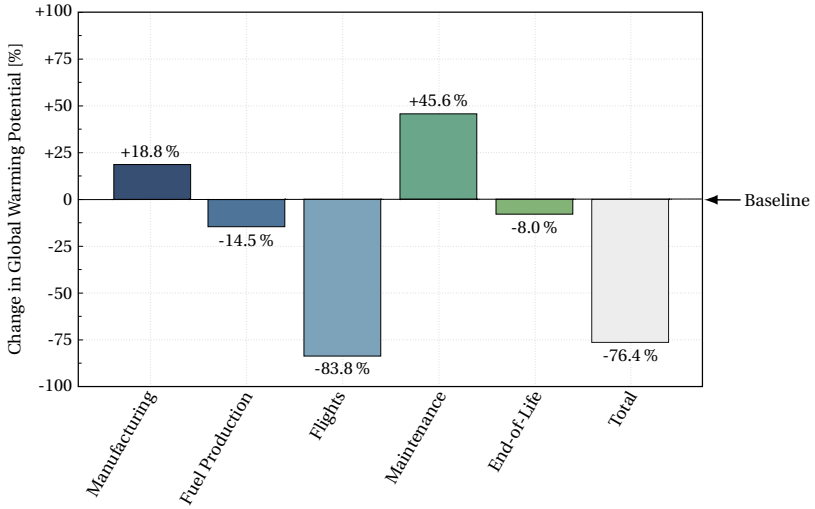
Table 5.2: Operational parameters of the baseline and MHEP aircraft over a lifetime of 25 years, including their relative deviations.

	Baseline	**MHEP**	**Delta**
Total Distance	5.39×10^7 km	5.27×10^7 km	-2.2 %
Total FC	40,137	39,272	-2.2 %
Total FH	70,255	67,995	-3.2 %

The LCA results of the impact category CC in terms of GWP are listed in Table 5.3 for both functional units. The results indicate, that the environmental performance relative to the baseline is not uniform across life cycle stages, but rather shows both increases and decreases, as illustrated in Figure 5.3.

Table 5.3: LCA results over all life cycle phases for the kerosene-powered baseline and the MHEP aircraft over a lifetime of 25 years. The results are presented both as totals over the entire lifetime and per ASK.

Life Cycle Phase	**Global Warming Potential** [tCO_2-eq./lifetime]		**Global Warming Potential** [gCO_2-eq./ASK]	
	Baseline	**MHEP**	**Baseline**	**MHEP**
Manufacturing	1,771	2,104	0.13	0.16
Fuel Production	131,617	112,513	9.77	8.54
Flights	1,128,699	182,357	83.80	13.84
Maintenance	1,523	2,217	0.11	0.17
End-of-Life	-505	-560	-0.04	-0.04
Total	1,263,105	298,631	93.77	22.67



5

Figure 5.3: Changes in the GWP of the MHEP aircraft compared with that of the baseline aircraft for each life cycle phase. The total result indicates the overall GWP difference across all phases.

Additional hydrogen subsystems increase production-related CC impacts by approximately 19 %. For most parts of the aircraft, the material composition is similar. The hydrogen tanks and fuel cell system entail large amounts of advanced material. The higher impacts associated with the production of these components are partially offset at the end of the aircraft's life through recycling and reuse, which reduces the need for primary material production. At the end-of-life stage, recovered materials can provide notable environmental benefits by 11 %. In the case of the MHEP concept, the reuse of critical materials within the fuel cell is the most significant factor.

The in-flight impacts account for by far the largest share of the environmental burdens for both aircraft concepts. Switching to green hydrogen promises significant reduction potentials. More than 83 % of the CC impact can be eliminated (see Figure 5.3) due to the replacement of fossil fuels and the reduction of in-flight combustion emissions of hydrogen compared to kerosene. However, this reduction potential is strongly dependent on the hydrogen production pathway. The production of fuel accounts for the second-largest contributor to the overall environmental impacts. While the CC impact per kilogram of hydrogen is almost 2.5 times higher than that of kerosene, hydrogen's higher energy content results in a lower fuel requirements per flight. It should be noted that the results are solely based on generic ecoinvent datasets and serve as indicative values. The environmental impact of hydrogen production strongly depends on the chosen hydrogen production pathways, electrolysis hubs, and underlying assumptions [282]. The dataset *market for hydrogen* represents a European market mix combining various hydrogen production routes (e.g., electrolysis) and transport to consumers. Therefore, the environmental impact results should be interpreted as indicative rather than pathway-specific.

Maintenance activities exhibit the largest relative increase in environmental impacts when comparing the hydrogen aircraft with the baseline. Although the increase amounts

to around 45.6 % (approximately 700 tCO_2-eq.), this contribution remains minor compared to the overall life cycle impacts (< 0.1 % of the total savings achieved by the MHEP aircraft). The higher values mainly reflect stricter safety and inspection requirements for cryogenic tanks, fuel cells, and sensors, which lead to increased maintenance complexity and downtime. Given the prospective nature of these technologies and the significant uncertainties in maintenance data, the following section examines the maintenance phase in greater detail, with particular focus on the contribution of individual hydrogen systems and the associated uncertainty ranges.

5.4.2. Environmental Impact of Maintenance

Over a 25-year lifetime, the conventional aircraft undergoes more than 48,000 maintenance events, resulting in approximately 62,000 hours of downtime, as highlighted in Figure 5.4. In comparison, the MHEP aircraft reaches over 72,000 hours of downtime. This reflects the higher complexity and longer duration of maintenance activities associated with new technologies (highlighted in light green).

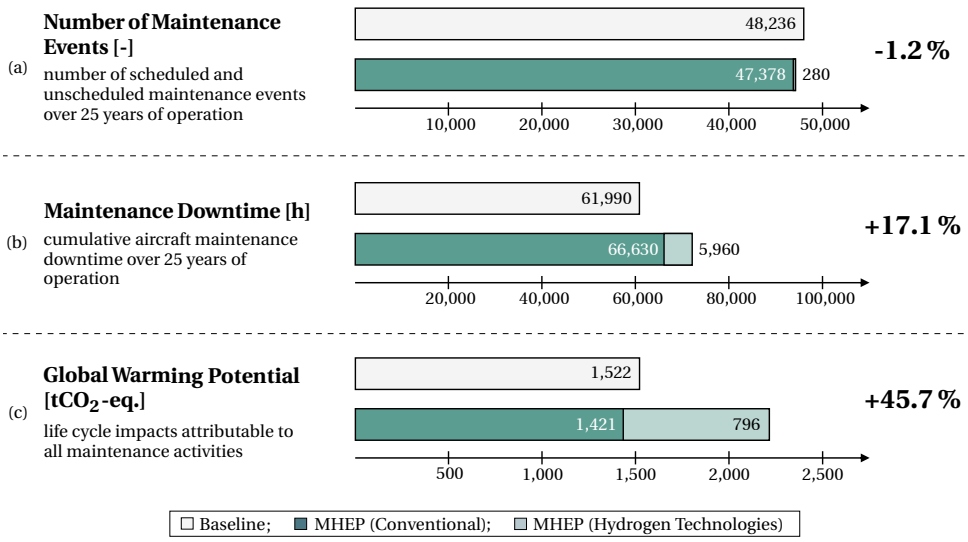


Figure 5.4: Comparison of the total number of maintenance events (a), total downtime due to maintenance (b), and overall environmental impact of all maintenance tasks (c) for the baseline (grey) and the MHEP (green) aircraft after an operating lifetime of 25 years. The light green area shows the respective share of the hydrogen technologies.

In total, 280 new maintenance tasks were defined specifically for hydrogen-related technologies, including maintenance activities for hydrogen tank, fuel cell system, and propulsion system. These inventories include all inputs associated with scheduled maintenance, such as energy, spare parts, and material demand. Despite the additional tasks, the overall lower utilisation profile of the MHEP aircraft suggests a slightly lower total number of maintenance events compared to the baseline, although this difference falls

within the uncertainty range of the data. This indicates that the environmental burden depends not only on the number of events, but also on the scope and intensity of the underlying activities. A detailed overview of all hydrogen-related maintenance inventories is provided in the supplementary material.

The main contributors to the increased environmental impact are primarily driven by extensive maintenance checks or the replacement of new components. For example, the MHEP aircraft may require approximately six fuel cell stack and two hydrogen tank replacements over its lifetime, depending on the underlying assumptions. However, considerable uncertainty exists in these estimates, primarily due to limited data on component lifetimes (i.e., replacement intervals) and information concerning the efforts during the replacement activities. To provide a clearer understanding of this variability, Figure 5.5 depicts the distribution of the GWP associated with the main replacement tasks. The distributions show considerable spread, reflecting the uncertainty of the underlying input parameters.

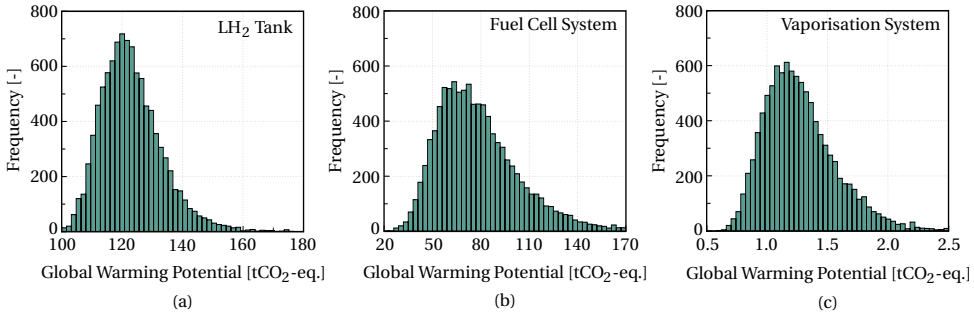


Figure 5.5: Uncertainty distribution of GWP results of the main replacement tasks: LH_2 tanks (a), fuel cell system (b), and vaporisation system (c), calculated using a Monte Carlo simulation with 10,000 runs.

While the distributions of individual replacement tasks highlight the variability of specific maintenance events, it is their cumulative influence over the aircraft's service life that ultimately determines the environmental impact of maintenance. Figure 5.6 shows the temporally resolved maintenance impacts over the lifetime. Figure 5.6a compares the accumulated GWPs of the baseline aircraft (black line) with those of the MHEP aircraft (green line). The jumps in the baseline curve reflect major engine overhauls, which are primarily characterised by long workshop durations and the replacement of LLPs. Similar patterns can be observed in the maintenance curve of the MHEP aircraft, although additional increases in environmental impact arise from novel maintenance activities.

Figure 5.6b illustrates the difference in maintenance impacts between the two aircraft types (green line) with the shaded area indicating the possible range of these impacts. As described in Section 5.3.3, the frequency of events (interval), task-specific downtime, and task scope were treated as uncertain parameters. For each parameter, upper and lower bounds were specified, and the range of uncertainty was evaluated using a scenario-based minimum–maximum approach. As shown in the figure, the possible range of maintenance impacts is significant. Notably, this range is skewed towards higher values: even in the optimistic scenario (lower edge of the green shaded area), the MHEP aircraft

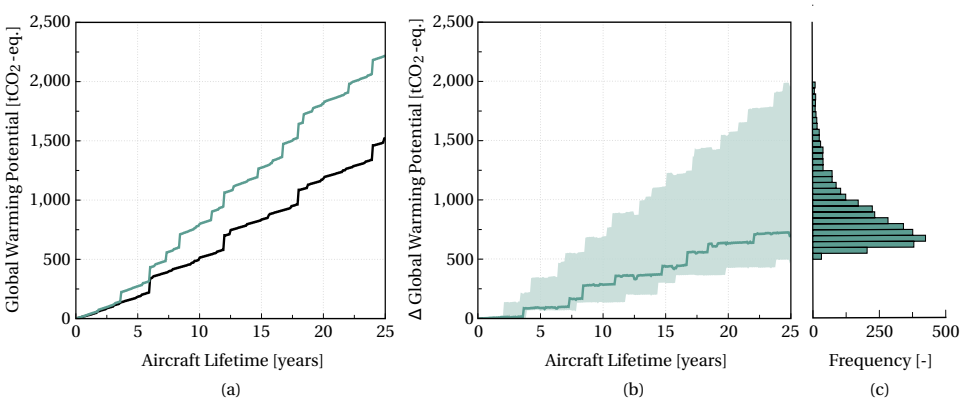


Figure 5.6: Temporally resolved LCA results of maintenance activities over 25 years. Subfigure (a) shows the cumulated GWP for the baseline aircraft (black line) and the MHEP aircraft (green line). Subfigure (b) shows the cumulative GWP delta between the baseline and the MHEP aircraft (calculated as baseline minus MHEP) over the aircraft lifetime. The shaded area represents the minimum–maximum range from the simulations, while (c) shows the frequency distribution of the cumulative GWP delta at the end of the aircraft lifetime.

requires more maintenance than in the baseline scenario, while in the pessimistic case, the difference can be more than twice as large as in the deterministic scenario.

Figure 5.7 presents a waterfall diagram illustrating the contribution of the newly introduced hydrogen technologies to the environmental impacts associated with the maintenance of the MHEP aircraft. To better understand the contribution of individual components to the overall uncertainty, minimum–maximum simulations are carried out for pa-

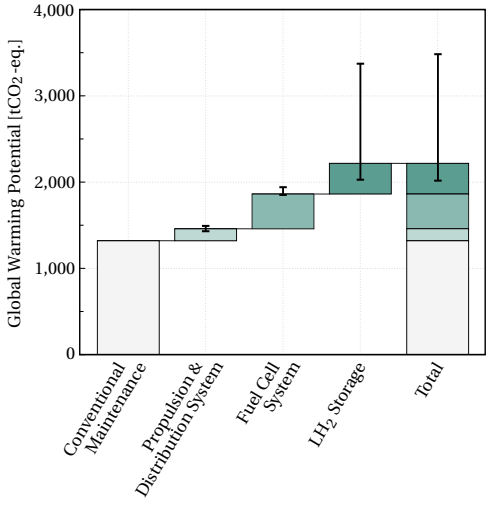


Figure 5.7: Waterfall diagram showing the GWP of all maintenance activities associated with the MHEP aircraft. The contribution of new hydrogen technologies is highlighted in green, and error bars represent the uncertainty in the maintenance impact.

rameter subsets related to the hydrogen storage, the fuel cell system, and the propulsion and distribution system. This approach allows the identification of the main contributing factors and an assessment of their relative impact on the maintenance LCA results. The black error bars indicate the corresponding uncertainty ranges, derived from the minimum and maximum values observed in the simulations.

The largest share stems from all conventional maintenance activities that are independent of the hydrogen technologies. These include, for example, overhauls of the airframe or functional tasks. MRO activities of the hydrogen propulsion and distribution system account for only 6.3 % of the overall maintenance impact. Since only the newly added vaporisation system is subject to uncertain parameters in this subsystem, the associated uncertainty (see error bars) remains relatively small. Maintenance of the fuel cell system and the hydrogen storage contribute 403.5 tCO_2-eq. and 355.2 tCO_2-eq., respectively. For both component groups, the main contributors are the replacement of subsystems. The uncertainty is particularly large for the hydrogen tanks, primarily due to the number of replacements assumed over the aircraft's lifetime. The deterministic tank lifetime corresponds to two replacements over the aircraft's lifetime. Due to the lack of reliable empirical data on actual tank lifetimes, this value should be regarded with caution.

Considering all impact categories of the EF 3.1 LCIA method, a consistent pattern emerges. Within all impact categories, the environmental impact of the MHEP maintenance is higher than that of the baseline aircraft. Figure 5.8 presents the deterministic results (diamond markers) together with the possible ranges resulting from input vari-

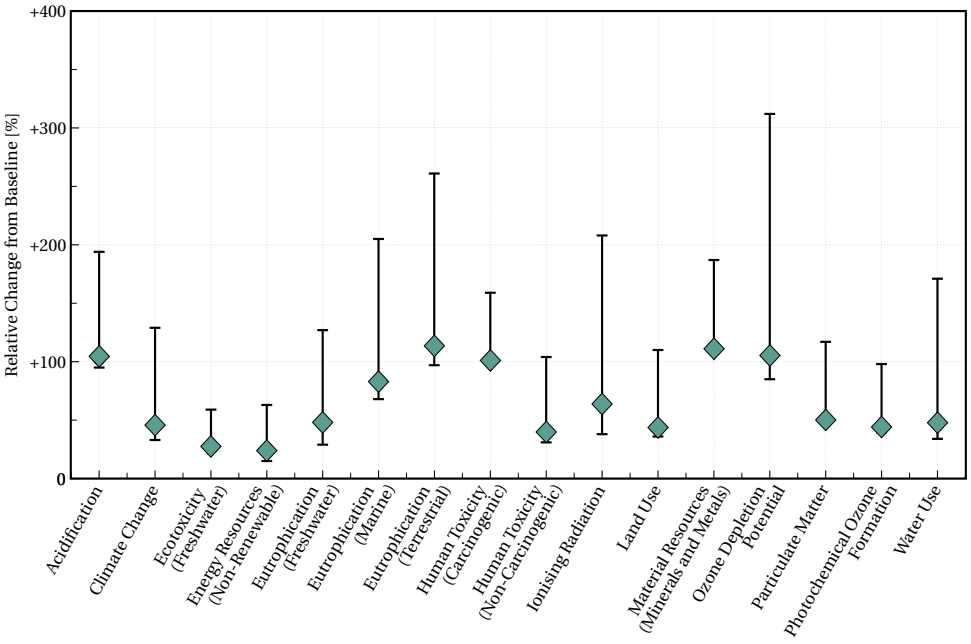


Figure 5.8: Deterministic LCIA results and uncertainty ranges for maintenance of the MHEP aircraft relative to the baseline aircraft (baseline = 0 %) across all EF 3.1 impact categories.

ability. The deterministic values indicate increases of roughly 30 % in some categories (e.g., ECF and FETP) and more than 100 % (i.e., more than double of the baseline impact) in categories such as AP, Terrestrial Ecotoxicity (TEP), MM, or ODP.

The error bars in Figure 5.8 represent the minimum–maximum range derived from Monte Carlo simulations. They reveal a pronounced asymmetric uncertainty: downward deviations are small, suggesting that true values are unlikely to be significantly lower than the deterministic estimates, whereas upward deviations are substantially larger, indicating a considerable potential for higher impacts across most categories. This asymmetry primarily results from the lognormal distributions applied in the Pedigree-based uncertainty modelling, which inherently produce skewed outcomes. However, some parameters, including operational ones, were modelled using alternative approaches rather than the Pedigree method.

5.5. Discussion

Despite recent advances in hydrogen integration in aviation, significant technical and methodological challenges remain, particularly regarding fuel storage, maintenance implications, and uncertainty quantification. While hydrogen has the potential to reduce in-flight climate impacts by more than 83 %, the environmental burdens in other life cycle phases increase by up to 45 %. Nevertheless, the savings achieved during flight operations significantly outweigh these additional impacts, although the magnitude of this benefit depends on the underlying assumptions. Additional aircraft components, such as hydrogen tanks or fuel cell systems, increase manufacturing efforts. The maintenance phase in particular is associated with varying maintenance requirements that influence environmental outcomes. However, MRO activities are still rarely considered in the literature, even though they represent a measurable, if comparatively small, contribution to the overall environmental impacts of emerging aircraft technologies.

A key aspect of this study was the inclusion of uncertainty quantification. Since hydrogen technologies in aviation are highly prospective and no real-world data are yet available, all inventories and simulation inputs rely on a large number of assumptions. Probabilistic approaches, including Monte Carlo simulations and the Pedigree matrix, were applied to capture uncertainty ranges of various parameters. For maintenance, the largest uncertainties are related to the hydrogen tanks, as both their production and the associated replacement activities are particularly material- and energy-intensive. This aligns with other recent economic assessments of these technologies [270] and highlights the significant knowledge gap in integrating new technologies from a maintenance perspective. Our study indicates that uncertainties in environmental assessments can lead to underestimations of potential impacts, which could be substantially larger than predicted, for instance, in hydrogen tank maintenance. Such blind spots could be relevant for industry stakeholders and policy makers, as overlooked maintenance burdens lead to increased environmental impacts that warrant consideration in future assessments.

The combination of the discrete-event simulation framework LYFE^2 with LCA provides insights beyond conventional static LCAs in aviation. By enabling temporally resolved and detailed consideration of maintenance and operations, this dynamic analysis allows technologies to be evaluated and compared on an operational basis, even before

real-world deployment. Operating the same flight schedule under consistent boundary conditions, novel technologies, or alternative aircraft designs can be assessed at a highly granular level. Moreover, considering multiple environmental impact categories for the maintenance phase shows that the overall pattern is very similar to that observed for CC, indicating consistent directional trends across categories. In some categories, the pessimistic input data could lead to LCA results up to four times higher compared to the baseline aircraft.

The inventories applied in this study are based on detailed datasets from laboratory and simulation studies. However, inconsistencies between the underlying modelling approaches and applied simulation methods represent a limitation of the analysis. For a more realistic evaluation of emerging technologies, future studies should prioritise the collection of empirical data on component lifetimes and maintenance efforts for hydrogen-specific technologies. Additionally, the integration of prospective datasets and technological learning curves to better capture the evolving environmental performance of these systems over time should be considered [305]. Furthermore, global sensitivity analyses or comprehensive scenario analyses provide a solid basis for identifying potential improvements in the analysis. Beyond the aircraft itself, the processes involved in hydrogen production, distribution, storage, and liquefaction critically shape overall environmental outcomes.

5.6. Summary and Outlook

This study conducted an LCA of a hydrogen-powered aircraft in comparison to a conventional kerosene-based aircraft. While hydrogen can cut overall climate impacts by over 75 % across its life cycle, this advantage is accompanied by important trade-offs: increased maintenance efforts, longer downtimes, and more frequent component replacements can raise the environmental burden of maintenance activities by up to 45 %. Although maintenance contributes only a minor share to the overall life cycle impacts, the relative differences between aircraft concepts are substantial. The hydrogen tank and its operational lifetime emerged as particularly critical elements, highlighting significant knowledge gaps. These gaps have important implications for industry stakeholders and policymakers, as maintenance-related environmental impacts may be higher than anticipated. Considering maintenance in environmental assessments can therefore support the development and implementation of emerging aircraft technologies by identifying maintenance-related challenges and improvement potential at an early stage.

Future research should consider the global availability of renewable hydrogen as not all regions will be able to provide sufficient quantities for aviation. Spatio-temporal LCA could provide useful insights in this context. Moreover, maintenance for hydrogen technologies, while contributing a relatively small share of overall environmental impacts, should not be neglected. The complexity and resource intensity of these tasks should consistently be considered in assessments of hydrogen-powered aviation. Finally, global sensitivity analyses may help better capture non-linear interactions and identify the most influential parameters in prospective assessments of hydrogen-powered aviation.

Chapter 6

The Value of Time: How Turnaround Strategies Shape Sustainability Trade-offs in Hybrid-Electric Aircraft

Hybrid-electric aircraft are widely considered a promising near-term low-emission solution for aviation, yet their environmental benefits may come with increased reliance on critical raw materials. The extent to which battery charging time and turnaround strategy influence this trade-off remains poorly quantified. Here, we combine life cycle assessment, criticality analysis, and semi-empirical battery degradation modelling to show that longer turnaround times substantially reduce the total number of batteries required over the aircraft lifetime. For example, a turnaround time of 100 minutes can reduce global warming potential by up to 78 % relative to conventional kerosene aircraft while minimising additional critical raw material demand. These benefits come at the cost of lower aircraft utilisation. Our results identify battery demand as the primary driver of environmental performance and resource use, indicating that the long-term viability of hybrid-electric aviation depends as much on operational decisions as on technological advances.

This chapter has been submitted as:
Rahn, Antonia; Wolf, Jan-Alexander; Hoff, Tim; Albrecht, Pascal; Pohya, Ahmad Ali; Sprecher, Benjamin; Balkenende, Ruud; Dransfeld, Clemens; Wende, Gerko. "The Value of Time: How Turnaround Strategies Shape Sustainability Trade-offs in Hybrid-Electric Aircraft". Nature Energy, 2026.

6.1. Introduction

Decarbonising aviation represents one of the most difficult challenges in the global effort to mitigate climate change [306]. Despite continuous efficiency improvements, the total carbon footprint of the aviation sector continues to grow, driven by annual traffic increases of around 4-5 % [4]. At the same time, concerns over resource scarcity and supply constraints have increased in recent years due to growing demand for critical materials across multiple industries [307]. The transition towards low-carbon aviation shifts environmental burdens from fuel combustion to the production, use, and end-of-life management of emerging technologies. Consequently, assessing future aircraft concepts requires considering not only GHG emissions but also the demand for critical raw materials across the entire life cycle. The urgency to reduce environmental impacts simultaneously managing material criticality has never been greater and requires rapid innovation and systemic transformation of the aviation sector.

Full-electric and hydrogen-powered aircraft are considered key pathways with large emission reduction potential by 2050 and beyond [308]. However, these aircraft concepts face long development timelines and significant technological and operational challenges that hinder their deployment in the near term [3]. Hybrid-electric aircraft, which combine electric propulsion with conventional engines, offer a promising transitional solution by balancing performance with emissions reduction [1, 309]. While this concept reduces reliance on fossil fuels, its environmental performance depends on the battery system, whose production, replacement, and end-of-life treatment over the aircraft's life drive much of the overall impact [310, 311].

A central driver of the battery-related environmental impacts is the charging strategy, which strongly affects battery degradation [312–314]. Charging times influence degradation mechanisms and thereby determine battery cycle life. This, in turn, governs the frequency of battery replacements and the number of required batteries over the aircraft lifetime. Previous studies have assessed the life cycle impacts of hybrid-electric aircraft [293] or optimised battery charging infrastructure [315]. However, no study has systematically investigated how battery degradation dynamics influence both environmental performance and critical material demand.

In this study, we assess the life cycle implications of battery use in a PHEP aircraft concept. Rather than evaluating technological feasibility alone, we focus on how operational decisions shape the environmental performance of the aircraft over its lifetime. Additionally, by considering multiple energy carriers, such as conventional kerosene and synthetic fuels, we examine how energy choices contribute to its life cycle impacts. To support this analysis, we present an integrated life cycle simulation framework that captures the interactions between flight operations and maintenance events, while also incorporating a semi-empirical battery degradation model. Our findings reveal a fundamental trade-off: while hybrid-electric propulsion reduces life cycle GWP impacts, it increases battery-related critical material demand. This trade-off is driven by turnaround time and charging strategies. By coupling LCA, CA, and battery degradation modelling, this study identifies the conditions under which hybrid-electric aircraft can serve as an effective transitional pathway towards lower-emission aviation.

6.2. Results

The section first analyses the results regarding the operational consequences of different turnaround strategies in terms of battery degradation, aircraft utilisation, and battery demand. Based on these findings, the corresponding results of the LCA and CA are presented.

6.2.1. Charging Strategies and Impact on Battery Lifetime

A crucial consideration in the operation of battery-powered aircraft is how the turnaround procedure and the charging process of the battery modules should be managed [316]. There are two basic approaches to this with distinct operational implications: On-board charging during turnaround or battery swapping with pre-charged modules. With the on-board charging approach, the batteries remain in the aircraft and are fully charged for the next flight during the grounding period without extending the anticipated turnaround time. To meet the ambitious operating targets in commercial aviation and to avoid disruptions in the flight plan, fast charging of high capacity batteries using high current rates is typically required to meet operational constraints [315]. In addition to charging and grid infrastructure challenges [317], this results in higher battery stress, faster ageing, and more frequent module replacement. In contrast, battery swapping allows charging under optimal conditions and decoupling from turnaround times, but requires significantly more battery modules and storage capacity at fleet-level [317]. The relative performance of charging strategies is therefore governed by their impact on battery degradation and the resulting module demand over the aircraft lifetime.

Batteries are subject to several operational parameters that influence complex degradation mechanisms and contribute to capacity loss [318]. One operational parameter affecting multiple different degradation modes is the charge/discharge rate (C-rate), a measure that describes the rate at which a battery is charged or discharged relative to its maximum capacity [319, 320]. Higher C-rates result in accelerated capacity fade due to mechanical damage of active battery particles and contribute to various degradation mechanisms [321–323]. To evaluate the two basic turnaround strategies with regard to these influences, the capacity fade of four different charging scenarios (0.2C, 0.5C, 1C, and 2C), as depicted in Figure 6.1, was examined using a semi-empirical degradation model (see Section 6.4.3). Under fast charging at 2C (charging time: 27.5 minutes), the

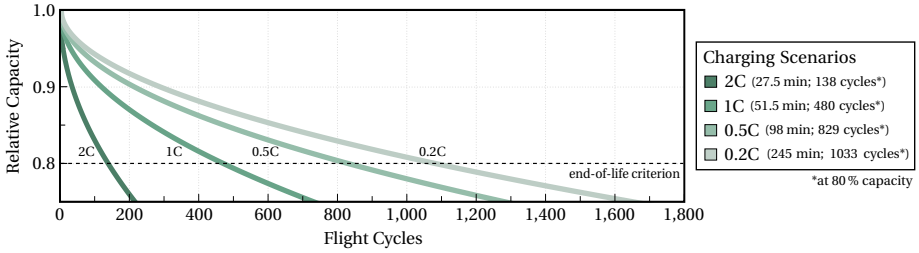
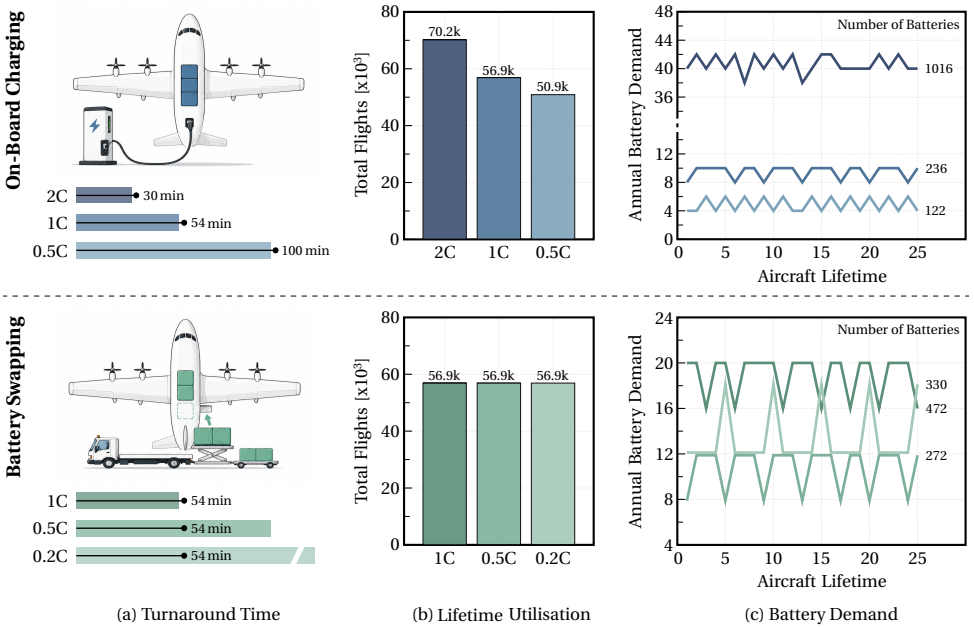


Figure 6.1: Relative battery capacity over FCs for charging scenarios ranging from 0.2C to 2C. The dashed line indicates the end-of-life criterion at 80 % remaining capacity.

battery reaches its end-of-life criterion after only 138 FCs. By contrast, at 0.2C (charging time: 245 minutes), the battery remains operational for 1,033 FCs, corresponding to approximately six months of operation. These differences directly affect the feasibility of alternative turnaround strategies and determine subsequent battery replacement requirements over the aircraft lifetime.

6.2.2. Turnaround Strategies and Battery Demand

Figure 6.2a illustrates the two turnaround strategies considered in this study. Under the on-board charging strategy, batteries remain installed in the aircraft and must be recharged between flights. Charging rates of 2C, 1C, and 0.5C are considered, resulting in approximately 30[8], 54, and 100 minutes of turnaround time. Battery swapping decouples battery charging from aircraft operations and allows for a constant turnaround time of 54 minutes. The discharged batteries are replaced during the turnaround and are charged off-board. This allows for much lower and degradation-friendlier C-rates of 0.5C and 0.2C. The 1C charging scenario was additionally evaluated for battery swapping to facilitate a direct comparison between turnaround concepts under identical charging conditions.



(a) Turnaround Time (b) Lifetime Utilisation (c) Battery Demand

Figure 6.2: Schematic representation of the on-board charging and battery swapping turnaround strategies and the resulting turnaround times (a); aircraft utilisation over a 25-year operational lifetime for different turnaround strategies and charging scenarios (b); and annual battery demand over the aircraft lifetime resulting from battery degradation and additional battery sets required for battery swapping (c).

[8]The 30-minute turnaround time is an ambitious design target; in practice, other ground operations such as boarding and servicing may result in longer turnaround times, depending on the operator.

Using a discrete-event life cycle simulation framework (see Section 6.4.4) over an operational lifetime of 25 years, we simulated aircraft utilisation under the two turnaround strategies. With a standard turnaround time of 54 minutes, the aircraft operates approximately 56,900 FCs (see Figure 6.2b). Faster charging at 2C increases utilisation to almost 70,200 FCs, whereas slower charging at 0.5C results in approximately 10 % lower utilisation. Battery swapping keeps utilisation constant at 56,900 FCs.

These changes in degradation behaviour, turnaround time, and aircraft utilisation directly affect the number of required batteries throughout the aircraft lifetime. Figure 6.2c shows the distribution of battery demand per year for the different charging scenarios. Under an on-board charging scenario with C-rates of 2C, 508 battery replacement events occur over the aircraft lifetime. Given that two battery modules are installed simultaneously (one in each propulsion pod, see Section 6.4.1), replacements are performed in pairs, corresponding to 1,016 batteries. This large battery demand results from the accelerated degradation observed under high C-rate charging conditions, which substantially increases replacement frequency. In the 1C and 0.5C scenarios, the number of batteries per aircraft is reduced to 236 and 122, respectively.

In contrast, battery demand under the swapping strategy is governed not only by degradation but also by the need for additional spare batteries. Here, the total number of batteries increases significantly as tight flight schedules require multiple battery sets to ensure immediate flight continuation (see Figure 6.2c). With an average flight time of 105 minutes, slow charging with C-rates of 0.5C requires two sets of batteries per aircraft. In contrast, a 0.2C charging rate leads to charging times of 245 minutes corresponding to three battery sets per aircraft. In 25 years, this results in 336 batteries, an increase of more than 20 % compared to the slow charging scenario. It is assumed that sufficient charged batteries are available at each airport to avoid operational constraints.

These results demonstrate that battery demand arises from fundamentally different mechanisms under the two turnaround strategies. For on-board charging, battery demand is primarily driven by degradation-induced battery replacements, whereas under battery swapping it is determined by the number of battery sets required for continuous aircraft operations.

6.2.3. Sustainability Assessment of a Single Battery Module

Before scaling to the full aircraft lifetime, we first characterise the sustainability performance of a single Nickel-Manganese-Cobalt (NMC) lithium-ion battery module, as its production and replacement govern both the environmental impacts and resource efficiency of the overall system.

6.2.3.1. Environmental Impacts

The following assessment applies an environmental LCA (see Section 6.4.6) across 16 midpoint impact categories. Results are presented for a baseline scenario based on a European electricity mix in 2025 [324]. The environmental impacts of battery production vary widely across components and impact categories, revealing that no single component dominates across all impact categories (Figure 6.3). For instance, while the anode and cathode contribute to more than 60 % in all impact categories, the cell container and

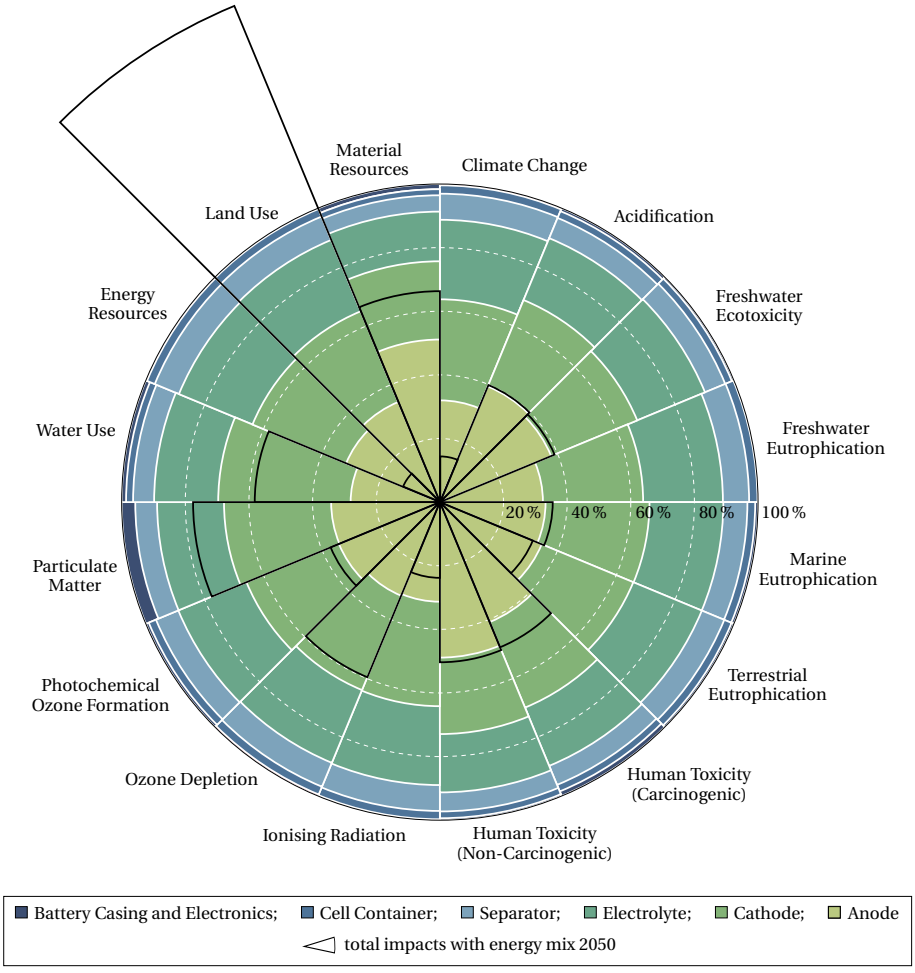


Figure 6.3: LCA results shown as a polar diagram across multiple midpoint impact categories based on EF 3.1. The system boundaries include raw material extraction, material processing, and energy use for manufacturing and assembly of the battery module. Coloured segments represent the relative contributions of individual battery components to identify trade-offs between impact categories. The black line indicates environmental impacts assuming a projected European electricity scenario in 2050.

casing show relatively low impacts (maximum 5 %). Copper is the most influential material in the anode, whereas nickel, cobalt, aluminium, and lithium dominate the impacts of the cathode. Despite the relatively low mass of the cell container and battery casing, the composites used in these components contribute substantially to certain impact categories, such as particulate matter, human toxicity, and material resources.

To assess the influence of future electricity pathways, the LCA was additionally performed for a projected European electricity scenario in 2050, represented by the black line in Figure 6.3. The observed change in environmental impacts can be primarily attributed to the decarbonisation of electricity generation and the elimination of asso-

ciated upstream fossil fuel processes (see Section 6.4.5). The only category in which the environmental impact increases is land use, due to the need for large areas of land for photovoltaic or wind energy plants [257]. This reflects a broader pattern of burden-shifting between impact categories, which becomes particularly relevant when transitioning to low-emission aviation.

6.2.3.2. Resource Efficiency

Nine of the 36 critical and strategic raw materials defined by the European Union [325] are used in the presented battery module. In terms of mass, copper accounts for the largest share (approximately 21 %). To assess resource criticality and supply risks associated with the raw materials used, the Integrated Method to Assess Resource Efficiency (ESSENZ) methodology [326, 327] was applied (see Section 6.4.7). The results are shown in Figure 6.4 and demonstrate that the cathode dominates all supply risk and social impact categories. This is attributable to the large amount of nickel (comprising 99 % of the total nickel mass) and lithium (97 %), along with cobalt. The remaining components are primarily composed of non-critical polymers and materials with lower supply risk, such

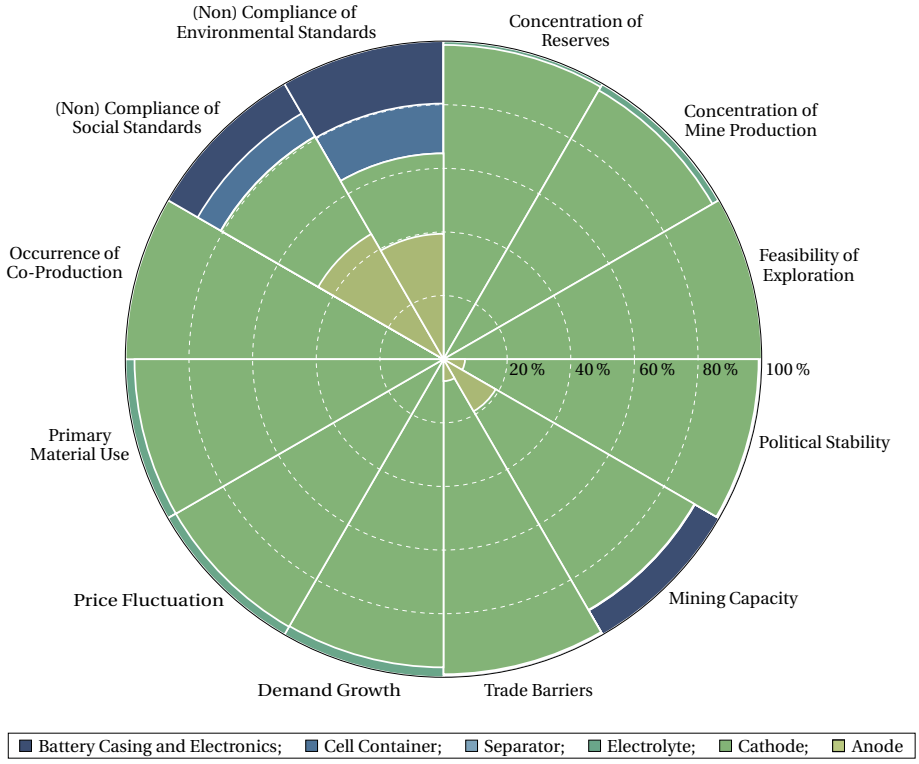


Figure 6.4: CA based on the ESSENZ methodology, illustrating supply risk and social impact indicators associated with the raw materials used in the battery module. The electricity mix is not a contributing factor to criticality and is therefore not represented in the polar chart.

as aluminium and iron. The compliance categories reveal a more differentiated pattern, as these impacts are distributed across a broader range of materials. Cobalt remains a major contributor to social risk indicators associated with the cathode. Unlike the LCA results, the CA is independent of the electricity mix, as it reflects only the properties of the raw materials.

6.2.4. Trade-offs Between Environmental Impact and Resource Criticality

While the detailed battery results provide crucial insights at component-level, we extend the assessment to the full aircraft life cycle, comparing the PHEP aircraft against a conventional kerosene reference of equal seat capacity over a 25-year lifetime. Results are normalised per ASK and reported as relative deviations from the reference. We focus on GWP and Concentration of Mine Production (CMP) across the three energy scenarios (see Section 6.4.5). The outcomes for all other impact categories are included in the supplementary material.

Figure 6.5 maps each charging scenario relative to the reference aircraft in two dimensions: the change in GWP (x-axis) against the change in CMP (y-axis). This results in a two-dimensional space in which the bottom-left corner represents the most favourable combination of climate benefit and low risk of resource concentration, whereas the top-right corner entails a climate penalty and higher resource concentration. In our study, almost all scenarios lie within the beneficial GWP zone and differ primarily along the vertical CMP axis. The arrows show how each kerosene scenario shifts as the electricity mix changes from 2025 to 2050. This reduces the GWP across all scenarios, while their resource criticality remains largely unchanged, being mainly determined by battery production. The use of PtL leads to an additional relative benefit in terms of GWP, as indicated by the white markers.

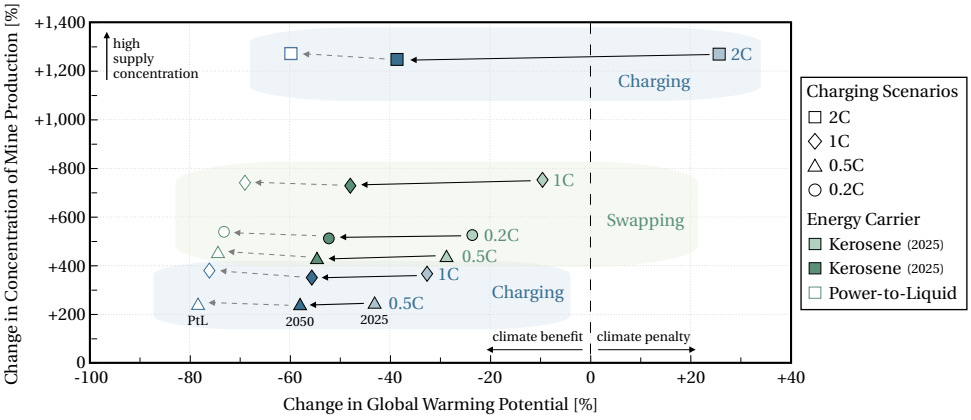


Figure 6.5: Change in GWP versus change in CMP for each charging scenario. The bottom-left region indicates combined climate and supply-risk benefits; the top-right a climate penalty and higher supply concentration. Marker shape denotes the charging scenario and the colour indicates the energy carrier. The arrows indicate the shift from kerosene (2025) to kerosene (2050) and further to PtL.

The charging scenarios do not form a uniform group. At low to moderate C-rates (0.5C and 1C), on-board charging is slightly more beneficial than battery swapping in terms of resource criticality. This stems from the higher number of batteries required for swapping, as multiple spare batteries are needed. In the 2C on-board charging scenario, resource criticality rises sharply and is approximately 13 times higher than for the baseline aircraft. This is due to the high charging rate, which shortens battery lifetime and thus increases the demand for batteries. In terms of environmental impacts, the 2C charging scenario also performs worst and would even increase GWP relative to the baseline under the kerosene 2025 scenario. The greatest environmental benefit is achieved by the 0.5C charging scenario, with an improvement of 78 %. Despite the longer turnaround time and the associated lower aircraft utilisation, the environmental impact per ASK is lowest here.

In Figure 6.6, these relative delta values from the trade-off diagram are converted into a normalised score, with the globally most favourable scenario assigned a value of 1 and the least favourable a value of 0. GWP and CMP are normalised separately, so that on-board charging and battery swapping are directly comparable across both dimensions. The hatched areas represent the scenarios that have not been considered. On-board charging at 0.5C achieves the maximum value (1) in both dimensions and thus represents the most favourable scenario, outperforming even the best swapping option at the same C-rate. GWP and CMP take almost identical values in every scenario, indicating no conflict between climate impact and resource criticality. This is because both indicators are largely determined by the number of batteries required over the life cycle; a scenario with fewer battery replacements therefore improves both dimensions simultaneously.

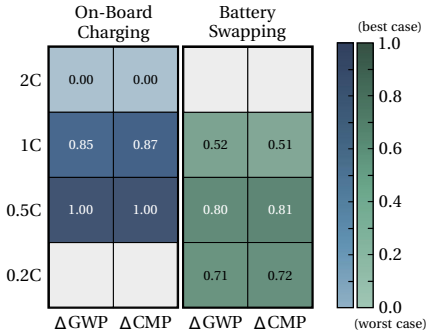


Figure 6.6: Normalised score (0 = least favourable, 1 = most favourable) for GWP and CMP, derived separately for each indicator across all scenarios. Hatched cells indicate scenarios that were not considered.

6.3. Discussion and Conclusion

While hybrid-electric aircraft concepts can act as an intermediate solution for aviation, their environmental benefit is strongly shaped by charging time and turnaround strategy. Especially in terms of CC, we achieved reduction potentials of up to 78 % per ASK compared to conventional kerosene-powered aircraft. This effect, however, strongly depends

on the availability of a renewable electricity mix and synthetic fuels, since battery use can otherwise offset possible GWP reductions. In terms of resource criticality, battery-electric aircraft inevitably increase supply concentration, as batteries contain significant amounts of critical raw materials. Minimising the total number of batteries is therefore a key design objective. An on-board charging scenario of 0.5C was identified as the most promising charging strategy. Yet, extending the turnaround time to 100 minutes reduces transport capacity by approximately 10 %, leading to fewer daily rotations per aircraft and constraining operational scheduling. Conversely, battery swaps can keep turnaround times short, while extending battery lifetime through slower C-rates. This effect is quickly offset when multiple battery sets are needed.

Our results highlight that the overall sustainability of PHEP concepts depends not only on the aircraft technology itself, but on how batteries are produced, used, and reused over their life cycle. Research on batteries should therefore not only focus on energy densities, but on material cycles, lifetimes, and second-life applications. For operators and airport stakeholders, turnaround times are important levers to shape sustainability of aircraft. By accepting slight reductions in transport performance, and consequently also economic viability, environmental impacts can be reduced substantially.

Due to the complex nature of the analysis, our study is subject to several limitations and assumptions. First, we considered a simplified flight schedule based on average flight segments to identify general trends and the effects of different battery charging strategies. Future studies should incorporate real-world flight schedules to better capture operational variability and its impact on system performance. Furthermore, different locations can have significant impacts on the considered electricity mix [328]. Studies should therefore consider region-specific electricity mixes to assess the sensitivity of battery-electric aircraft performance to local energy conditions. A further set of limitations concerns the battery modelling. Our C-rate scaling is based on a limited set of data points, so absolute lifetime estimates should be interpreted with caution. Apart from that, the battery lifetime estimation is based on degradation characteristics for state-of-the-art lithium-ion technology. With technological developments, battery chemistries could lead to improved service life. Furthermore, we only applied a simplified 50 % end-of-life allocation based on battery capacity. Appropriate recycling strategies and second-life applications may lead to more insights into usability and especially material criticality of batteries. Another assumption was that there were always enough spare batteries after every flight for the battery swapping scenario. The logistics of airlines and airports concerning battery availability are complex and have been investigated in numerous recent studies [329, 330]. These considerations are essential for the practical implementation of novel aircraft concepts at fleet-level.

Despite these limitations, the combination of discrete-event life cycle simulation and battery degradation modelling provides a level of temporal resolution that static assessments cannot offer. By capturing individual replacement events and their secondary effects on flight schedules and aircraft downtimes, the approach links battery ageing directly to life cycle impacts. The subsequent LCA and CA translate these into environmental impacts and resource-related risks relevant for aircraft design and operational planning. Concluding, hybrid-electric concepts can reduce near-term emissions, but they shift part of the burden to material demand. Improving the overall sustainability of

aviation therefore involves more than substituting one technology for another: it requires managing the trade-offs that each transitional pathway introduces. This calls for closer alignment between the aviation and energy sectors, for instance, through incentives for new energy carriers and certification frameworks for new technologies. Ultimately, sustainable, resilient, and competitive aviation will need a portfolio of complementary technologies

6.4. Methods

The following sections describe the aircraft and battery designs, the battery degradation model, the considered energy carriers, the simulation approach, and the assessment methods that were used in this study.

6.4.1. Aircraft Design

The PHEP aircraft is based on a design concept developed within the EXACT project, undertaken by DLR [331]. Our model incorporates the main characteristics and architecture proposed in this project and is adapted to align with the specific battery system and operational assumptions of this assessment. Figure 6.7 presents the PHEP concept, highlighting the two battery modules.

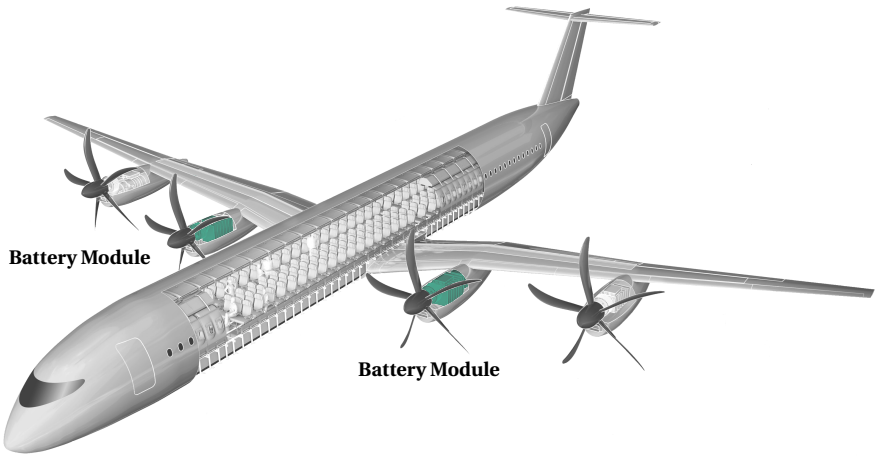


Figure 6.7: PHEP aircraft concept from the EXACT project. The two battery modules in the inner nacelles are highlighted in green (source: DLR, internal documentation).

The aircraft features two battery modules, each located in the inner nacelles, which are always replaced simultaneously during maintenance events. Battery sizing is based on an average mission with a range of 400 NM and a flight duration of 105 minutes, corresponding approximately to a flight from London to Zurich. For the considered mission profile, propulsive energy is supplied by the batteries during all flight phases

except the cruise phase, which is powered solely by the two gas turbines. Consequently, parts of the flight mission are operated without direct in-flight combustion emissions. Additional information on the flight mission and power split between the battery and gas turbines is provided in the supplementary material.

6.4.2. Battery Design

The battery system model is based on Albrecht et al. [332]. Cell characteristics are captured with an equivalent circuit model comprising a variable voltage source and a variable internal resistance (Rint model). The cell voltage V_{cell} is characterised by

$$V_{cell} = V_{OC}(SoC) - R(SoC) \cdot I_{cell} \tag{6.1}$$

where I_{cell} denotes the cell current [333, 334]. The parameters used for the open circuit voltage V_{oc} and internal resistance R are dependent on the State of Charge (SoC). They correspond to a LG18650HG2 cell and are taken from Campagna et al. [335]. The required number of cells in series n_{series} is calculated by comparing the maximum cell voltage with the target battery system voltage of 800 V. The required electric mission energy of around 10.4 MWh divided by the number of batteries ($n_{bat} = 2$) determines the number of cells in parallel $n_{parallel}$. The resulting battery system power P_{bat} can be calculated by:

$$P_{bat} = V_{cell} \cdot I_{cell} \cdot n_{series} \cdot n_{parallel} \cdot n_{bat} \tag{6.2}$$

With these assumptions, each of the two battery modules requires a total mass of 11,700 kg, assuming an energy density of 444 Wh/kg at system-level [336]. Considering that battery operation in extreme SoC-ranges below 10 % and above 90 % leads to increased degradation, the battery is oversized by 20 % with respect to the required mission energy. One battery module consists of 191 and 2,517 cells connected in series and in parallel, respectively. A simplified parametric cooling system keeps the average battery temperature from rising more than 7 °C during all flight and charging segments. This requires elevated heat transfer coefficients during charging, assuming a separate liquid cooling circuit is available

The battery model was then applied to the mission profile for this aircraft concept. The simulation covers one discharge-charge cycle and four different charging rates. Under fast charging conditions, the battery can be charged in 27.5 minutes, requiring a 2C charging rate. In a moderate scenario, the battery is charged in 51.5 minutes, requiring a C-rate of 1C and a turnaround time of 54 minutes. Slow charging takes up to 98 minutes (0.5C). Alternatively, the battery can be swapped and charged outside the aircraft. Here, C-rates of 1C, 0.5C, and 0.2C are considered, with the 0.2C scenario requiring a charging time of 245 minutes. Table 6.1 lists the charging scenarios and associated turnaround times. The battery capacity, the discharge profile, and the SoC interval (0.1-0.9) were maintained across all simulations. The resulting cell parameters serve as inputs to the degradation model described in the following section.

Table 6.1: Overview of the turnaround strategies and charging scenarios considered for the PHEP aircraft.

Turnaround Strategy	Charging Scenario	C-Rate	Charging Time	Turnaround Time
On-Board Charging	Fast	2C	27.5 min	30 min
	Moderate	1C	51.5 min	54 min
	Slow	0.5C	98 min	100 min
Battery Swapping	Moderate	1C	51.5 min	54 min
	Slow	0.5C	98 min	54 min
	Super-Slow	0.2C	245 min	54 min

6.4.3. Battery Degradation Modelling

To investigate degradation behaviour under different operational conditions, we apply a semi-empirical degradation model. Semi-empirical models combine physical analyses with experimental observations and have proven to successfully estimate battery lifetime in operational settings [337]. The model established by Clarke and Alonso [338] and Schmalstieg et al. [339] was set up for commercial high-energy 18650 lithium-ion cells with NMC cathode material and is therefore well suited for our battery system. The experimental data used for the model was gathered through accelerated ageing tests on more than 60 cells under various operating conditions [339]. The calendar and cyclic aspects of battery degradation were tested individually and their effects were then combined to determine the total ageing functions. Taking into account certain operating parameters, the model estimates the decrease in capacity and increase in internal resistance of the battery cells, which are considered as the main degradation effects.

As the required energy, in conjunction with capacity fade, represents the limiting factor, we focus on the capacity-driven ageing effect for determining the end-of-life of the battery [339, 340]. By applying a threshold on the remaining capacity as a usage limit, the analysis translates capacity fade into an end-of-life criterion for each scenario. Many studies define battery lifetime at 80 % of the initial capacity, a convention that originated from operational requirements in the automotive sector [341–344]. This work adopts the same threshold to ensure comparability across scenarios. To predict the remaining capacity over time, we apply the ageing function in Equations (6.3-6.5) of the model, whereas α_{cap} is a calendar ageing coefficient and β_{cap} is a cycle ageing coefficient.

$$E_{Fade} = 1 - \alpha_{cap}\, t^{0.75} - \beta_{cap} \sqrt{Q} \tag{6.3}$$

$$\alpha_{cap} = (7.543\, V - 23.75)\; 10^6\, e^{-\frac{6976}{T}} \tag{6.4}$$

$$\beta_{cap} = 7.348 \cdot 10^{-3} \left(\bar{V} - 3.667\right)^2 + 7.600 \cdot 10^{-4} + 4.081 \cdot 10^{-3}\, \Delta DOD \tag{6.5}$$

Based on parameter variations during the experimental tests [339], the capacity decrease is dependent on time (t in days), charge throughput (Q in ampere-hours), cell voltage (V in volts), operating temperature (T in kelvin), and linear cycle depth (Δ Depth of Discharge (DoD) in the range of 0-1). This ageing function includes the key parameters influencing degradation for our needs, although it does not cover the impact of the C-rate. Since all cycling tests for the model were conducted at a charge/discharge rate of 1C, the original model does not allow for any variation of this operating parameter. However, as discussed in Section 6.4.2, the C-rate is a crucial variable in order to investigate the influence of different turnaround and charging strategies on battery degradation for our study. Although alternative degradation models account for C-rate effects [345, 346], the present model has been established in our internal workflows and validated for similar applications [347, 348]. Therefore, we modify the ageing function to reflect this effect without changing the basic structure of the model.

Since variations in C-rate mainly affect cycle ageing, we consider the implementation of a scaling multiplier for the corresponding term of the function to be appropriate. This allows us to account for the effect of a value higher than 1C leading to increased cyclic degradation intensity and a value lower than 1C leading to reduced intensity, compared to the original model structure. As a first approximation, interactions between C-rate effects and other degradation parameters are not considered. In reality, the degradation effect of the C-rate on lithium-ion cells is likely to be more pronounced at high DoD values and might also depend on the operating temperature [323, 349]. To incorporate the scaling term, we follow the semi-empirical approach of the model and combine empirical degradation data from battery cells with physical dependencies. For this purpose, Liu et al. [350] provides capacity fade data for lithium-ion cells in which the effect of different C-rate values can be observed in isolation. Even though these data were originally obtained for cells with a different cathode material, they provide a good basis for our approach. With a constant temperature of 303.15 K and a DoD value of 0.8, the cell degradation was investigated under conditions that are very well suited to our use case, thus keeping the above-mentioned potential interactions between the C-rate impact and other influencing parameters low. The degradation intensity varies between charge and discharge [351], with charge-rate effects being approximately three times higher [352].

When it comes to physical degradation mechanisms driven by C-rate effects, two different trends can be identified. A low to medium C-rate range is mainly associated with strong polarisation effects, whereas high C-rate values and, in particular, charging are more sensitive to solid electrolyte interphase growth and lithium plating [323, 345, 351, 353]. Mathematically, these effects are often described by the power law or exponential law. Taking these physical dependencies into account, we set up a fitting curve for the capacity fade data using non-linear optimisation with a gradient-based method. This identifies the exponential pattern as the most accurate fit, while for simplicity we assume the same pattern for the charge and discharge rates. Finally, we introduce weighting factors to incorporate different degradation intensities for charge and discharge rates and set a C-rate value of 1C as ground base for our scaling term. The modified ageing function is then given by Equation (6.6-6.7), whereas $E_{Fade,C}$ represents the term for scaling the cyclic degradation intensity due to changes in charge rate C_{Ch} and discharge rates C_{Dis}.

$$E_{Fade} = 1 - \alpha_{cap}\, t^{0.75} - \beta_{cap} \sqrt{Q}\, E_{Fade,C} \tag{6.6}$$

$$E_{Fade,C} = \frac{3}{4} e^{0.8408\,(C_{Ch}-1)} + \frac{1}{4} e^{0.8408\,(C_{Dis}-1)} \tag{6.7}$$

To reflect an actual operating scenario, we apply the modified degradation model by iterating through different flight phases, while simulating charging processes and operational pauses. Here, we take into account operational cell parameters, system design parameters, and flight data. After each flight, the remaining capacity is calculated and compared with the specific end-of-life criteria to determine whether the battery needs to be replaced. These replacement events are then passed to the life cycle simulation framework.

6.4.4. Life Cycle Simulation

We used the DLR in-house LYFE^2 framework, a modular discrete-event life cycle simulation tool, to assess environmental impacts over the aircraft's full lifetime. LYFE^2 divides the entire life cycle of an aircraft into individual events. These events comprise the aircraft production, flight operations, scheduled and unscheduled maintenance events, turnaround times, and a final end-of-life treatment. Each event is associated with a set of attributes, such as environmental impacts and material inventories, which can be evaluated across the entire lifetime. The event-based approach captures dynamic effects within the life cycle and analyses operational dependencies, constraints, and subsequent implications, which cannot be assessed using static LCA approaches.

For this study, LYFE^2 requires the aircraft-specific flight plan, maintenance schedule, and turnaround times as inputs. The flight plan is resolved to individual flights with their mission profile and airport locations, while the maintenance schedule defines the planned check intervals. For the PHEP aircraft, the battery degradation model is coupled with LYFE^2 and determines when battery replacement events are triggered based on the remaining battery capacity. A detailed description of all functions within LYFE^2 is presented in Ramm et al. [302]. The framework has been applied to several aircraft concepts [284, 291]. All input parameters are summarised in the supplementary material.

6.4.5. Energy Carrier

Two fuel-based energy carriers are considered: Jet A-1 kerosene and synthetic fuel (PtL). Compared with kerosene, PtL fuels are produced from renewable feedstocks and green hydrogen, which significantly reduces net CO_2 emissions. In addition, previous studies have shown that PtL fuels may reduce high-altitude climate impacts and cleaner local emissions during combustion, while remaining compatible with existing aircraft engines and infrastructure [8].

The energy mixes used for aircraft and battery production, as well as for charging the batteries, are based on the European electricity mix taken from the GENeSYS-MOD 2.9

database with the Directed Transition 1.0 scenario [324]. The 2025 energy mix represents current energy sources, while the 2050 energy mix comprises mainly wind, photovoltaics, and hydropower. Combining the fuel types with the electricity mixes yields three energy scenarios: kerosene paired with the 2025 and the 2050 electricity mix, and PtL paired with the 2050 mix. PtL is considered only in combination with the 2050 electricity mix, as large-scale production is assumed to become feasible only in the long term. This allows a comparative assessment of how energy choices shape the climate impacts of hybrid-electric aviation.

6.4.6. Life Cycle Assessment

The environmental impacts are calculated using an LCA. LCA is a standardised approach to calculate a wide range of different environmental impacts throughout the entire lifetime of a product [21, 22]. The LCA starts with a goal and scope definition which sets the system boundaries and assumptions. The goal of this analysis is to quantify and compare the environmental life cycle impacts of a conventional kerosene-powered aircraft and a PHEP aircraft across multiple impact categories. Our assessment covers the environmental performance of both aircraft types across their entire life cycle, including aircraft manufacturing, fuel production and combustion across all flights, scheduled maintenance and battery replacements, and end-of-life processes. End-of-life impacts are accounted for using the credit for avoided virgin production [112]. For the PHEP aircraft, we additionally include the production impacts of all batteries over the aircraft lifetime. Batteries are replaced in aviation at 80 % remaining capacity due to safety regulations, but can continue operating in stationary applications until 60 % state of health. Assuming linear capacity fade, impacts are allocated equally between aviation and stationary use, yielding a 50 % impact allocation. Electricity consumption per flight is incorporated to capture operational energy demand. We consider a well-to-tank approach for the energy carrier. The functional unit per ASK is used to compare the two aircraft. This accounts for differences in aircraft utilisation arising from battery charging times. The climate impacts associated with flight operations are adopted from previous work [291], including both CO_2 and non-CO_2 effects. The present study does not further refine the underlying emission modelling.

The LCI includes all relevant materials and energy flows that are needed throughout the aircraft's lifetime. The inventory of the aircraft is derived from previous studies [172, 291] and adjusted to meet the aircraft characteristics. Battery data is taken from Ellingsen et al. [354] with manufacturing energy inputs from von Drachenfels et al. [355] and scaled based on battery mass and capacity. The inventory covers battery manufacturing and electricity supply, while logistics and transportation are excluded due to limited data availability. The inventory for the synthetic fuel is adapted from van der Giesen et al. [184] and produced from wind energy in Germany, with an equal share of onshore and offshore wind power. Inventory data were selected to ensure geographical and temporal representativeness consistent with the European operational context and the assessment period. We used ecoinvent 3.11 with the cut-off by classification system model [146] as background database. The entire LCI is provided in the supplementary material. The life cycle impacts for each impact category were then calculated by mul-

tiplying the inventory flows with the corresponding characterisation factors, following the EF 3.1 LCIA method [295]. For the trade-off analysis with the CA, only the GWP is considered.

6.4.7. Criticality Analysis

The CA is based on the same bill of materials and the same goal and scope definition as the LCA, including the system boundaries, the functional unit, and the assumptions. In this way, both assessments rely on a consistent inventory of material inputs, while addressing different sustainability dimensions. Whereas the LCA quantifies environmental impacts over the life cycle, the CA evaluates material demands and the associated resource-related and societal risks of aircraft and battery system production.

For this purpose, the ESSENZ methodology was applied [326]. ESSENZ is a life cycle-based method for assessing resource efficiency and criticality at product-level and complements the LCA by considering categories related to physical and socio-economic availability as well as societal acceptance of abiotic resources. The material inventory was linked to the corresponding ESSENZ characterisation factors in order to determine the criticality profile of the battery module and the aircraft. While the full set of ESSENZ indicators is provided in the supplementary material, the analysis focuses on the CMP as the primary indicator for supply risk.

6.4.8. Trade-Off Analysis

To ensure that the scenarios are comparable across both indicators, the relative deviations from GWP and CMP are each scaled to a value between 0 and 1 using min-max normalisation. The best (x_{best}) and worst (x_{worst}) values across all charging and swapping strategies serve as reference points:

$$S_i = \frac{x_{worst} - x_i}{x_{worst} - x_{best}} \tag{6.8}$$

where S_i is the normalised score of a scenario for indicator i and x_i is its relative deviation. A value of 1 thus corresponds to the globally most favourable scenario, while a value of 0 corresponds to the globally least favourable scenario. Both indicators are normalised separately in order to highlight any potential conflicts of interest.

Chapter 7

General Conclusion

7.1. Main Findings and Research Contributions

This dissertation investigated the challenges of assessing the environmental performance of emerging aviation technologies in the context of increasing system complexity, long aircraft service lifetimes, and evolving decarbonisation pathways. To better capture the dynamic interactions between aircraft operation, maintenance, and environmental impacts, a discrete-event LCA framework was developed and applied to two emerging aircraft concepts: a hydrogen-powered MHEP aircraft and a battery-electric PHEP aircraft.

While LCA is an established methodology for environmental evaluation, most assessment frameworks face challenges when being applied to new aircraft concepts due to technology-specific knowledge gaps and limited data availability. In addition, existing methodological approaches are often unable to capture dynamic operational and maintenance behaviour throughout the aircraft life cycle. Consequently, important environmental trade-offs remain hidden and may result in misleading conclusions regarding the environmental performance of aircraft technologies. The developed discrete-event LCA framework enables a more detailed and temporally-explicit assessment of environmental impacts by capturing these interactions throughout the aircraft life cycle.

Across all studies within this dissertation, the findings confirm that the operational phase remains the dominant contributor to the environmental impact of aircraft, which is consistent with findings in the literature. However, focusing on this life cycle phase alone is insufficient for the environmental assessment of emerging aviation technologies. In particular, burden-shifting effects can occur both between life cycle stages and between environmental impact categories. The studies in the methodological part of this dissertation (Chapters 2-4) further highlight that maintenance activities, the production of energy carriers, and other ground-based processes can significantly influence environmental impacts and should therefore be systematically included in LCA studies. In addition, the inclusion of aviation-specific climate factors, such as non-CO_2 effects and their dependence on flight routes, strengthens the robustness of environmental assessments. This is especially relevant for highly globalised industry sectors such as aviation.

The studies in Chapters 5 and 6 further demonstrate the high complexity and the presence of secondary effects associated with new aircraft technologies, e.g., maintenance-induced downtime or turnaround times. Environmental impacts can shift across life cycle phases and involve new trade-offs in terms of infrastructure requirements, component lifetimes, and replacement cycles. Uncertainties can become particularly large when evaluating future-oriented technologies. Through a holistic assessment across multiple impact categories, this dissertation provides insights into integrating new technologies into future aviation systems and cascading effects that may arise during this transition.

Overall, this dissertation makes three major contributions. Firstly, it advances LCA for aviation by combining it with discrete-event simulation. This enables the representation of dynamic processes throughout the aircraft life cycle and their consequential effects on environmental impacts. Secondly, it demonstrates the environmental relevance of previously underrepresented aspects, in particular, MRO processes. Although maintenance contributes only a relatively small share to overall life cycle impacts, it can strongly influence the operational feasibility and environmental benefits of aircraft technologies, particularly for emerging concepts. Thirdly, it illustrates that the framework can support

the environmental evaluation of emerging aircraft technologies under realistic operational conditions. In this way, the dissertation contributes both to the methodological advancement of environmental LCAs and to the general transition towards more sustainable aviation. The results show that environmental assessments should be incorporated into the development of new aircraft technologies starting from the earliest design phases to guide technology development towards environmentally robust solutions.

7.2. Addressing the Research Questions

In the following, the RQs of this dissertation are addressed individually.

RQ 1: How can discrete-event simulation be applied within life cycle assessment to provide a more comprehensive evaluation of environmental impacts across all life cycle phases of an aircraft?

The results of Chapter 2 demonstrate that discrete-event simulation can be integrated into LCA as an event-based modelling framework that represents individual flight operations and maintenance activities over the entire lifetime of an aircraft. In contrast to static LCA approaches, which are generally based on average parameters, the discrete-event approach enables the analysis of different event types and their interrelationships. Thereby, operational variability and dynamic maintenance-related interactions can be captured across the entire life cycle. The detailed approach makes it possible to depict individual life cycle stages in greater depth than has been possible in the literature to date.

A comparison of the assessment results with those from the literature shows that applying the discrete-event LCA approach produces highly comparable results. This provides a solid foundation for the subsequent studies in this dissertation. At the same time, the study clearly indicates that the approach requires a high level of data granularity and increases the importance of aviation-specific LCIs as well as uncertainty and sensitivity analyses.

RQ 2: What are the environmental implications of aircraft maintenance activities, and how can life cycle assessment methods capture these previously overlooked impacts?

Chapter 3 deals with the environmental impacts of aircraft maintenance activities, as these are still vastly underrepresented in traditional LCAs. Maintenance is mandatory to ensure airworthiness and long service life and should therefore not be neglected. The results of the analysis show that, across all impact categories, maintenance accounts for a comparatively small share of the overall life cycle impacts of conventional aircraft. Nevertheless, maintenance remains a relevant phase - not least because of the high number of maintenance events throughout the aircraft's service life and the variety of associated activities and environmental impacts. To capture these impacts, a more detailed representation of individual maintenance activities within the LCI was required, including the modelling at task- and component-level, maintenance intervals, material flows, and energy demand. The study shows that a combination of top-down approach on life cycle-level with a detailed bottom-up analysis of individual maintenance tasks

is a suitable approach to provide an overview of the entire MRO phase. At the same time, the need for improved aircraft-specific inventory data and a better representation of unscheduled maintenance activities was emphasised.

Another key finding from Chapter 3 is that maintenance effects are not evenly distributed over each year in the lifetime. Especially in years with heavy maintenance checks or engine and landing gear shop visits, environmental implications can be substantially higher. In these years, longer aircraft downtimes can also affect the transport capacity. Furthermore, the environmental impact of maintenance activities depends mainly on the energy consumption of maintenance equipment and facilities as well as the production of spare parts. Routine and recurring activities, such as daily inspections, can have a significant cumulative impact despite their short duration. Heavy inspections and the replacement of components (e.g., LLPs) make a significant contribution, particularly in material-related impact categories [226]. Environmental reduction potentials in maintenance can thus be achieved, for example, through improved resource management in MRO processes and the use of more renewable energy during maintenance procedures [255].

RQ 3: How can incorporating non-CO_2 effects and operational scenarios improve the accuracy within life cycle assessments of aircraft?

The study in Chapter 4 shows that integrating non-CO_2 effects into LCA significantly improves the representativeness of environmental impacts in aviation. Since non-CO_2 effects contribute roughly two thirds to the total climate effects of aviation in the atmosphere, this aspect should not be overlooked [109]. In particular, operating parameters, such as flight altitude, routing, and adjusted flight networks, have a major influence on climate effects. Thus, the climate impact can vary significantly compared to assessments that are based solely on aggregated emission inventories.

By coupling the developed discrete-event LCA with a climate response model, the study enabled scenario-based comparisons of different aircraft types, i.e., turbofan and turboprop configurations, under different operating conditions. In addition, the climate impact of different fuel types, such as conventional kerosene and PtL, could be assessed beyond their direct CO_2 emissions. The overall LCA results show that the turboprop aircraft has a better environmental performance compared to the turbofan aircraft, despite its lower flying velocity and higher maintenance implications. In addition, the results are consistent with findings in the literature suggesting that new fuel types can offer significant reductions in climate change impacts. Consequently, incorporating non-CO_2 effects and realistic operational scenarios substantially improves the robustness and representativeness of aviation LCAs.

RQ 4: What are the environmental impacts and associated uncertainties of new maintenance activities in hydrogen-powered aircraft, and how do they shape the overall life cycle footprint?

The first application study in this dissertation investigates the environmental impacts and associated uncertainties of new maintenance activities for hydrogen-powered MHEP

aircraft. The results of Chapter 5 show that the use of hydrogen technologies can significantly reduce overall environmental impacts over the entire life cycle compared to conventional kerosene-powered aircraft. Yet, these benefits come with relevant trade-offs in other life cycle stages. In particular, the production and maintenance of additional components, such as LH_2 tanks or fuel cell systems, lead to higher on-ground impacts. Additionally, new MRO requirements, including longer and more frequent maintenance downtimes, can lead to changes in operation that could not previously be adequately analysed and considered. The LH_2 tank proves to be a particularly critical component, as its useful service life in aircraft remains uncertain and both its production and replacement are highly material- and energy-intensive.

The study further highlights that the quantification of uncertainties is an essential aspect in the assessment of novel aircraft concepts. Current analyses are heavily based on assumptions due to the prospective nature of these technologies. By applying probabilistic approaches, including Monte Carlo simulation and Pedigree-based uncertainty characterisation, the study has shown that maintenance-related impacts can be significantly underestimated in deterministic assessments. Discrete-event life cycle simulation greatly simplifies the integration of these uncertainty parameters. Consequential effects can thus be represented and analysed. The results emphasise the importance of explicitly considering uncertainty aspects in LCA and improving the projected inventory data of future aircraft technologies.

RQ 5: What are the environmental impacts and critical raw material demand of plug-in hybrid-electric aircraft, and how does turnaround time shape this trade-off?

The outcomes of the PHEP aircraft study in Chapter 6 show that battery-powered concepts can significantly reduce environmental life cycle impacts compared to conventional aircraft. Yet, the results are highly dependent on the underlying energy system and operational constraints, as carbon-intensive electricity production can offset a significant proportion of the potential environmental benefits. By combining life cycle simulation with battery degradation modelling, the developed approach captures both the battery replacement events and the indirect effects on turnaround times and number of FCs. The study demonstrates that these secondary effects have a significant impact on life cycle outcomes and need to be explicitly considered in environmental assessments.

While flying with hybrid-electric propulsion can reduce operational emissions, the large amount of batteries and their high share of critical raw materials increase the relevance of criticality aspects and circularity effects. The accompanying CA further demonstrates that potential trade-offs between environmental benefits and material supply risks should be explicitly considered to provide a more comprehensive assessment. The analysis thus shows that environmental performance is not determined by propulsion efficiency alone, but by the complex interplay of aircraft operation, charging strategy, battery lifetime, and energy source.

Overall, the findings of this dissertation underline that the developed discrete-event LCA framework enhances the accuracy of environmental assessment studies. It enables a more detailed representation of operational and maintenance dynamics, including

secondary effects, across the overall aircraft life cycle. The framework was successfully applied to two emerging aircraft concepts with different technological characteristics and operational constraints. Across all articles in this dissertation, the outcomes highlight that burden-shifting effects can be minimised by detailed consideration of all life cycle phases. Taken together, this dissertation underlines, that a combination of multiple technologies and measures will be necessary to achieve sustainable aviation.

7.3. Limitations

From a methodological perspective, the discrete-event LCA approach enables a high degree of granularity. However, this level of detail is strongly dependent on data availability and the quality of datasets. A substantial number of assumptions had to be made throughout all studies in this dissertation. Where inventory data was unavailable, missing inputs were modelled by the author and, where necessary, estimated using proxy data. Although these assumptions were documented transparently in the supplementary materials of each study, they inevitably introduce uncertainty into the results. In addition, regional differences in ground-based datasets were considered whenever possible. However, due to the highly globalised nature of aircraft supply chains and operations, integrating region-specific datasets was not feasible in all cases.

Time-specific datasets are essential when assessing aircraft systems over long time horizons as temporal changes in the LCI can otherwise lead to over- or underestimation of environmental life cycle impacts. Owing to the limited availability of prospective datasets, future-oriented developments could only be incorporated to a limited extent. However, the discrete-event LCA approach is well suited to represent temporal aspects of environmental impacts, as both background inventory changes and the timing of individual life cycle events can be incorporated explicitly [257].

The results are highly sensitive to the boundary conditions and input data defined in the life cycle simulation, such as flight schedules, maintenance intervals, and turnaround times. Especially for new aircraft technologies, for which no historical reference data is available for validation, this may affect the robustness of the outcomes. For this reason, Chapter 5 includes an uncertainty analysis, which improves the environmental assessment of hydrogen-powered aircraft maintenance. However, due to the high computational efforts, uncertainty treatment could not be implemented at the same level of depth across all studies. Additionally, a semi-empirical degradation model for batteries was used and integrated into the discrete-event simulation framework (Chapter 6). This model was introduced to better represent uncertain replacement intervals for batteries in hybrid-electric aircraft. Nevertheless, limitations remain here as well, particularly with regard to operational conditions and replacement characteristics. Furthermore, some extensions of the assessment framework, such as the climate response model, were adopted from existing studies. The contribution of this dissertation lies not in the development of these individual models, but in their integration into the LCA framework.

Finally, this dissertation primarily focused on the assessment of individual aircraft. Real-world implementation of such concepts may depend strongly on fleet-level effects and infrastructure scaling. These aspects were largely beyond the scope of the present studies, but are essential for evaluating and enabling the broader transformation of the

aviation sector. Future research should therefore address these system-level interactions more explicitly. With increasing fleet penetration, future studies should further examine end-of-life strategies for aircraft and individual components. The meaningful integration of such strategies may offer additional environmental improvement potentials that are currently underestimated.

7.4. Recommendations

Based on the findings of this dissertation, the following recommendations are provided for the research community, LCA practitioners, and aviation stakeholders. They reflect the methodological and practical implications of the developed framework and advance environmental assessment approaches and the transformation to sustainable aviation.

The following recommendations identify key priorities for future research and methodological development in aviation-related LCAs:

- Future research should further advance and streamline dynamic LCAs, such as discrete-event approaches, by developing standardised modelling workflows, modular inventories, and openly available data. This will reduce implementation effort and improve reproducibility.
- As discrete-event LCA offers a higher temporal and process-related resolution than conventional LCA approaches, it requires significantly more detailed inventory data. Since the LCI phase is already one of the most time-consuming and labour-intensive phases of any LCA, future research should prioritise the development of detailed datasets, especially for aviation. This includes prospective datasets.
- Aviation is one of the most emissions-intensive modes of transport and one of the most globalised industries. For the assessment of aircraft, location- and altitude-dependent non-CO_2 effects should therefore be taken into account. This requires further development of existing LCIA methods and standards, for example through the integration of aviation-specific environmental impacts into existing or new impact categories.
- Since conventional LCA only partially captures circular economy strategies, future research should develop and validate circularity-oriented indicators and methodological guidance for their consistent integration into environmental assessment. This includes the consideration of end-of-life pathways (e.g., re-utilisation, recycling, and lifetime extension) as well as transparent allocation approaches and data requirements.
- The development and harmonisation of standards for environmental assessment methods and data collection should be further advanced. Greater methodological consistency will strengthen collaboration between industry and research and improve the comparability of results across organisations.

For LCA practitioners, the following recommendations are derived from this dissertation to inform best practices in planning, execution, and reporting of aviation-related assessments:

- Discrete-event simulation or other dynamic approaches should be integrated into LCA studies whenever products exhibit long and complex life cycles. Time-explicit modelling can reveal secondary effects (e.g., maintenance-induced downtimes) that remain hidden in conventional static assessments. Where full dynamic modelling is not feasible, practitioners should at least evaluate the robustness of results through scenario and sensitivity analyses.
- When considering future-oriented technologies, practitioners should use prospective datasets whenever available and define an assessment time frame to ensure consistency between foreground (e.g., energy density, efficiency) and background assumptions (e.g., electricity mix, supply chains). Data sources, projection methods, and the degree of technological maturity should be reported transparently, as results can be highly sensitive to assumed development pathways.
- Given the limited availability of data and the substantial number of assumptions that are required in LCA, uncertainty quantification should be systematically incorporated into the assessment. This is particularly important for comparative assessments of emerging technologies and prospective studies. Where uncertainty is dominated by future development pathways, scenario analyses should complement conventional uncertainty analyses.
- To enable a more comprehensive sustainability analysis, environmental LCA should be combined with complementary evaluation approaches. In particular, the integration of life cycle costing or CA can provide a broader sustainability perspective beyond environmental impacts. To avoid misleading comparisons, practitioners should align system boundaries and the functional unit across methods and clearly document any methodological differences.

These recommendations address aircraft designers, operators, maintenance providers, and airport stakeholders:

- Certification and approval of new aircraft technologies should incorporate life cycle-based considerations. To avoid burden-shifting effects, a broad set of environmental indicators should be considered rather than relying on individual performance metrics.
- In addition to fuel burn optimisation and cost efficiency, aircraft design should be driven by environmental considerations as such aspects can become an important factor for competitiveness. Consequently, such considerations should be systematically integrated into design trade-offs and decision-making processes.
- The introduction of new energy carriers in aviation, such as SAFs or hydrogen, requires early and coordinated action across airports and the energy sector. Airports should proactively plan and invest in the necessary infrastructure and operational capabilities, including fuelling and ground-handling procedures as well as staff training. Policymakers should create regulatory and financial incentives to ensure the availability of renewable electricity at airports and maintenance hubs.
- Flight scheduling should be aligned with the operational characteristics of different aircraft concepts to ensure that their potential can be realised effectively. For example, turboprop aircraft should be prioritised on short-haul routes, where the impact

of lower cruise speed on block time is limited and their fuel-efficiency advantages can be fully leveraged. Turnaround constraints need to be integrated into flight scheduling to avoid utilisation losses and operational disruptions.

- For emerging technologies, such as batteries or fuel cells, replacement processes and intervals require strategic consideration from an operational perspective. Their implementation has direct implications for turnaround times, maintenance capacities, and airport infrastructure requirements.
- Maintenance aspects should be considered early in the development process of new aircraft configurations. Being an essential element of continued airworthiness, MRO strongly influences the feasibility, safety, and regulatory compliance of new technologies. At the same time, maintenance-related constraints can become critical bottlenecks for implementation and should therefore be identified as early as possible in the design process.
- To reduce the environmental impact of maintenance processes, the main focus should be on energy consumption and spare part production. Switching to renewable energy sources can already result in considerable emission savings. In addition, the responsible use of spare parts should be prioritised. Lifetime extension measures should be encouraged, as they can reduce not only environmental burdens but also material demand through fewer component replacements.

Appendix A

Supplementary Material

Supplementary Material

The supplementary material accompanying Chapters 2-6 is available as a collection of datasets in 4TU.ResearchData, with one dataset for each publication. These datasets contain the simulation input data, model parameters, inventory data, and assessment results referenced throughout this dissertation. The collection is publicly available at:



https://data.4tu.nl/collections/0265f18a-7942-4f78-82e9-614fc93846fb

Supplementary Material for Chapter 2

The supplementary material for Chapter 2 is provided as the dataset *Supplementary Material accompanying the publication "Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment"*, comprising two spreadsheet files.

Life Cycle Inventory.xlsx

This file contains the complete life cycle inventory developed for the reference A320-type aircraft, including component-level inventory data as well as information on transportation, manufacturing, maintenance, and end-of-life processes. It provides the complete set of background processes from the ecoinvent 3.7.1 database and the corresponding literature that was used to model the inventory.

Life Cycle Impact Assessment Results.xlsx

This file contains the complete life cycle impact assessment results for all life cycle stages and impact categories. It further includes the event calendar generated with the discrete-event simulation framework LYFE and an overview of the EF 2.0 impact assessment methodology.

Supplementary Material for Chapter 3

The supplementary material for Chapter 3 is provided as the dataset *Supplementary Material accompanying the publication "Beyond Flight Operations: Assessing the Environmental Impact of Aircraft Maintenance through Life Cycle Assessment"*, comprising two spreadsheet files.

Life Cycle Inventory.xlsx

This file contains a detailed breakdown of the inventory for individual maintenance checks as well as an inventory of all maintenance tasks at the aircraft component-level. An extract from the maintenance planning document for the air conditioning system illustrates how individual tasks were modelled. The file further provides an overview of the background data used from the ecoinvent 3.9.1 database and the corresponding literature that was used to model the inventory.

Life Cycle Impact Assessment Results.xlsx

This file contains the life cycle impact assessment results at both component- and maintenance check-level, based on the EF 3.0 impact assessment methodology. It further includes the life cycle simulation results generated with discrete-event simulation framework LYFE for the scenario analysis.

Supplementary Material for Chapter 4

The supplementary material for Chapter 4 is provided as the dataset *Supplementary Material accompanying the publication "Quantifying Climate Impacts of Flight Operations: A Discrete-Event Life Cycle Assessment Approach"*, comprising two spreadsheet files.

Life Cycle Inventory.xlsx

This file contains a detailed life cycle inventory for the turbofan and turboprop aircraft, including manufacturing, maintenance, and end-of-life processes. It further provides a detailed overview of aircraft-specific alloys and materials, comprising both the material composition and the energy consumption required for their production. The file also includes an overview of the background data used from the ecoinvent 3.9.1 database and the corresponding references.

Life Cycle Impact Assessment Results.xlsx

This file contains the simulation set-ups generated with discrete-event simulation framework LYFE for the different scenarios of aircraft, flight schedule, and fuel type. It includes the complete results for all life cycle stages and impact categories, based on the EF 3.0 impact assessment methodology.

Supplementary Material for Chapter 5

The supplementary material for Chapter 5 is provided as the dataset *Supplementary Material accompanying the publication "Why Maintenance Matters in Environmental Life Cycle Assessment of Hydrogen-Powered Aircraft"*, comprising four spreadsheet files.

Life Cycle Inventory.xlsx

This file contains the complete life cycle inventory for the baseline aircraft and the hydrogen-powered mild-hybrid electric propulsion aircraft. Particular detail is provided for the inventories of the fuel cell system, the hydrogen tank, and the hydrogen propulsion and distribution system. The conventional maintenance checks for both aircraft, as well as the new hydrogen-specific maintenance tasks, are listed in detail. The file further provides an overview of the background data used from the ecoinvent 3.9.1 database and the corresponding references.

New Hydrogen Maintenance Checks.xlsx

This file provides an overview of all new maintenance checks associated with the hydrogen-powered aircraft, including their task description, maintenance type, maintenance interval and duration, and the corresponding life cycle inventory, along with all references used.

Life Cycle Impact Assessment Results.xlsx

This file contains the life cycle simulation set-up for both the conventional baseline and the hydrogen-powered aircraft, including an overview of the minimum–maximum calculation. All results are based on the EF 3.1 impact assessment methodology and are provided for all life cycle stages and impact categories.

Uncertainty Quantification.xlsx

This file provides an overview of the uncertainty parameters used in the calculations with the discrete-event simulation framework LYFE^2. For the three most critical replacement components (the hydrogen tank, fuel cell stack, and vaporiser) the Monte Carlo results of the cradle-to-gate life cycle assessments are further summarised. The maintenance inputs, including their associated uncertainty parameters serve as input for LYFE^2.

Supplementary Material for Chapter 6

The supplementary material for Chapter 6 is provided as the dataset *Supplementary Material accompanying the publication "The Value of Time: How Turnaround Strategies Shape Sustainability Trade-offs in Hybrid-Electric Aircraft"*, comprising three spreadsheet files.

Battery Degradation.xlsx

This file contains information on the battery chemistry and battery characteristics, as well as the corresponding battery data for an average flight mission of 400 nautical miles across different charging rates.

Life Cycle Inventory.xlsx

This file contains the life cycle inventory for the baseline aircraft and the plug-in hybrid electric propulsion aircraft, including a detailed inventory of the battery. In addition to the detailed material inventory, an overview of the critical raw materials used in the aircraft and the battery is provided. The file lists all background data from the ecoinvent 3.11 database, along with the corresponding references.

Life Cycle Assessment and Criticality Analysis Results.xlsx

This file contains the life cycle simulation set-up generated with discrete-event simulation framework LYFE^2. It further includes the life cycle assessment results, based on the EF 3.1 impact assessment methodology, and the criticality analysis results, based on the ESSENZ method, for the battery module and both aircraft, across all scenarios considered in the trade-off analysis.

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About the Author



Antonia Rahn was born in Potsdam, Germany, on 16 August 1993. She graduated in 2019 from Dresden University of Technology with a Diplom degree in Mechanical Engineering (equivalent to a Master's degree), specialising in Aerospace Engineering. During her studies, she was a scholarship holder of the sustainability-oriented Heinrich Böll Foundation. Early on, she combined academic work with hands-on aviation experience, for example, through internships and student assistant positions at Diehl Aviation or the DLR_School_Lab, where she conducted workshops and experiments with pupils on material selection for aircraft engines. She wrote her diploma thesis at Airbus in Bremen on the impact of maintenance downtime on airline profitability.

In 2020, Antonia joined the German Aerospace Center (DLR e.V.) in Hamburg as a research associate. She is part of the Product Lifecycle Management department at the Institute of Maintenance, Repair and Overhaul. Her work focuses on life cycle assessment of emerging aircraft technologies, which she has presented at international conferences and published in peer-reviewed journals. In parallel, she pursued her PhD at Delft University of Technology in collaboration between the faculties of Aerospace Engineering and Industrial Design Engineering. From January to July 2026, she was a visiting researcher in the Operations and Environment section within the Faculty of Aerospace Engineering.

Her academic path has been shaped by international experiences, including a teaching assistantship at the SENATI Institute in Lima, Peru, and volunteering exchanges in the Philippines and India. Outside academia, travelling and discovering new cultures remain among her greatest passions.

List of Publications

Journal Articles

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The future of aviation depends not only on the development of new technologies but also on a comprehensive understanding of their environmental impacts across the entire life cycle.

This dissertation presents a holistic discrete-event life cycle assessment framework that captures the operational complexity of flight and ground activites beyond conventional life cycle assessment approaches. Applied to conventional and emerging aircraft concepts, it supports early decision-making for sustainable aviation.



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