Transportation Research Part D 141 (2025) 104646

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Quantifying climate impacts of flight operations: A discrete-event life cycle assessment approach

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ARTICLE INFO

Keywords:
Life cycle assessment
Climate impact
Flight operations
Power-to-liquid
Discrete-event simulation
Maintenance

ABSTRACT

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 (LCAs) 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 LCA 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 LCA 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 LCA to achieve a more accurate understanding of aviation's environmental impact.

1. Introduction

Globally, the transport sector is a significant contributor to Greenhouse Gas (GHG) emissions, with aviation accounting for approximately 2-3% of global carbon dioxide (CO_2) emissions (European Union Aviation Safety Agency, 2022). 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 (Planès et al., 2021). The International Energy Agency (2021) 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 Sustainable Aviation Fuel (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

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https://doi.org/10.1016/j.trd.2025.104646
Received 26 August 2024; Received in revised form 4 February 2025; Accepted 7 February 2025
Available online 22 February 2025

Acronyms

ASK	Available Seat Kilometre
ATR	Average Temperature Response
CIC	Contrail-Induced Cloudiness
FC	Flight Cycle
FH	Flight Hour
GHG	Greenhouse Gas
GRIDLAB	Global Air Traffic Emission Distribution Laboratory
GTP	Global Temperature Potential
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LLP	Life Limited Part
LTO	Landing to Take-Off
LYFE	Life Cycle Cash Flow Environment
OEW	Operating Empty Weight
PAX	Passenger
PtL	Power-to-Liquid
SAF	Sustainable Aviation Fuel
TCM	Trajectory Calculation Module

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 (Lindner et al., 2019; Bailey et al., 2023).

Life Cycle Assessment (LCA) is a commonly used method for investigating and analysing the ecological impacts of aircraft (Rupcic et al., 2023; Timmis et al., 2014; Karakoc et al., 2024). However, this method often relies on aggregated data and lacks flexibility, which can lead to oversimplification, particularly when evaluating minor modifications to aircraft (Keiser et al., 2023). 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 (Albano et al., 2024). These challenges can result in various issues, such as limited comparability, reduced accuracy of the results, data quality concerns, and increased uncertainties (Whittle et al., 2024). Despite ongoing research on the significant impacts of flight operations, 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 nitrogen oxides (NO_X), which increase radiative forcing and differ from the long-term impacts of CO_2 emissions (Dahlmann et al., 2023). 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 (Niklaß et al., 2019). The quantification of non-CO_2 impacts necessitates comprehensive knowledge of aircraft trajectories, engine parameters, and atmospheric conditions (Dahlmann et al., 2021). Furthermore, standard Life Cycle Inventories (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 (Rupcic et al., 2023).

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 paper 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 paper is structured as follows: Section 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 3 provides the goal and scope definition, along with the LCI generation and a detailed description of the coupled assessment method. In Section 4, we present, analyse, and interpret the results of the scenario analyses in greater detail, followed by a concluding discussion (Section 5). Finally, Section 6 provides a summary of the paper and topics for future studies, for example, examining the integration of novel technologies.

2. Fundamentals

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 (Dahlmann et al., 2023; Bravo et al., 2022; International Civil Aviation Organization, 2017):

- 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. (2024), this paper 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.

2.1.1. Combustion technology

Fuel efficiency and, consequently, aircraft climate impact are highly dependent on combustion technology (Biemann et al., 2024). The two most common propulsion technologies for commercial aviation are turbofan and turboprop engines (Kuropatwa et al., 2022). Turbofan engines are commonly used on medium- and long-haul flights because of their optimal balance between cruising speed and fuel efficiency (Dahal et al., 2021). 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 (Babikian et al., 2002), 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 (Mattingly, 2000; Afonso et al., 2023), while their design characteristic is accompanied by longer flight durations and higher noise levels (Chirico et al., 2018).

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 (Filippone and Parkes, 2021). Furthermore, the fact that they typically operate in different flight profiles and at different speeds makes a comparison even more challenging. Graham et al. (2014) 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.

2.1.2. Sustainable aviation fuels

One approach to reducing the environmental impact of flight operations is to use SAF (Braun-Unkhoff et al., 2017). SAF can be synthesised through various processes, including Fischer–Tropsch, hydroprocessed esters and fatty acids, and alcohol-to-jet pathways (International Civil Aviation Organization, 2017). These methods rely on biological and renewable feedstocks, such as agricultural residues and nonfood crops. According to the International Air Transport Association (2023), 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 (Afonso et al., 2023), 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 (European Union Aviation Safety Agency, 2022).

In the literature, 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 (Afonso et al., 2023; Mussatto et al., 2022). 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) (van der Giesen et al., 2014). 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 (Batteiger et al., 2022). Notably, for medium and long distances, PtL fuels present a promising solution (Papantoni et al., 2021) 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 (Schäppi et al., 2022). Estimations of GHG emissions for PtL vary widely in the literature, ranging from 1 to 28 gCO_2-eq. per megajoule (Rojas Michaga et al., 2022; Micheli et al., 2022; Schmidt et al., 2016). Compared with other SAF production technologies, PtL generally has a lower environmental footprint, especially when it is produced using renewable energy sources (Barke et al., 2022b; Alhyari et al., 2019). However, there may be burden-shifting effects from Global Warming Potential (GWP) to other environmental indicators, particularly in terms of water, resource, and energy-related impacts (Papantoni et al., 2021). 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 (Rojas Michaga et al., 2022). 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 (Dahlmann et al., 2023). 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.

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 (Aircraft Commerce, 2013; Afonso et al., 2023). An efficient flight plan significantly contributes to overall operational performance, which in turn can lead to lower fuel consumption and reduced emissions (Kühlen et al., 2023).

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 (Krömer et al., 2024; Şafak et al., 2017; Jalalian et al., 2019). Furthermore, an improved combination of direct and connecting flights (Parsa et al., 2019; Krömer et al., 2024) and the restriction of flight altitude (Roosenbrand et al., 2022; Teoh et al., 2020) can further contribute to the sustainability of flight operations. As an example, the study of Noorafza et al. (2023) 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 (Williams et al., 2002)). 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 (Niklaß et al., 2021).

2.2. Life cycle assessment of flight operations

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* (Winther et al., 2023), which provides emissions for each Landing to Take-Off (LTO) cycle as specified in accordance with the International Civil Aviation Organization (2022). 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 (Krieg et al., 2012; Jordão, 2016). Other studies employ emission databases such as the *Emission Data Modelling System* (Chester, 2008; Chester and Horvath, 2009), the *Aviation Environmental Design Tool* (Liu et al., 2016), the IPCC database (Su-ungkavatin et al., 2023; Facanha and Horvath, 2006), the Piano-X database (Krammer et al., 2013), and the ecoinvent database (Lopes, 2010; Howe et al., 2013). All of these databases lack specific life cycle emission factors for new fuel types and their various production paths (International Civil Aviation Organization, 2022).

The literature emphasises that the climatic effects of in-flight emissions must be assessed differently than ground-level impacts. The studies of Cox (2018) and Johanning and Scholz (2013) 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 (2018) 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 contrails and induced cloud formation. The climate effects during flight operations are calculated via characterisation factors obtained from Fuglestvedt et al. (2010). 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 and Scholz (2013) extended the ReCiPe Life Cycle Impact Assessment (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 (Yang and Yao, 2025; Schreiber et al., 2024; Papantoni et al., 2021). 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 climate change, land use, water consumption, and electricity demand (Koj et al., 2019), as they capture the most important environmental aspects across the entire PtL fuel value chain. With respect to the climate change impact category, PtL fuels can achieve an approximately 50% reduction in CO_2 equivalents compared with conventional kerosene (Rojas Michaga et al., 2022). The reduction potential varies according to the length of the flight, with reductions ranging from 44% for short-haul flights to 56% for long-haul flights (Klenner et al., 2024). A study by Micheli et al. (2022) reported potential emission reductions of up to 88.9% with non-CO_2 effects excluded.

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 (Niklaß et al., 2019). Their non-linearity in relation to CO_2 and their spatial and temporal variability make the assessment of non-CO_2 effects highly uncertain (Scheelhaase et al., 2016). 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, NO_X emissions at flight altitudes of 8–12 km lead to complex non-linear chemical reactions in the atmosphere and the formation of cirrus clouds by contrails, which complicates the prediction and modelling of environmental impacts (Jungbluth and Meili, 2019; Lee et al., 2021). These 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 (Keiser et al., 2023).

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 (Grewe and Dahlmann, 2015). The majority of climate metrics are based on either radiative forcing or temperature change, including GTP and Average Temperature Response (ATR) (Levasseur et al., 2016). The most commonly employed indicator for assessing climate change is GWP. However, GWP has certain limitations in regard to the assessment of air transportation (Planès et al., 2021; Aamaas et al., 2013; Preston et al., 2012). One limitation is that it is not applicable to emissions with short lifetimes, such as NO_X, which can lead to the formation of ozone (Wit et al., 2005). Furthermore, GWP does not include the effects of contrails, which may result in an underestimation of the radiative forcing caused by aircraft (Intergovernmental Panel on Climate Change, 1999). Nevertheless, GWP is widely accepted in various climate policy contexts and is often used in emission reports, climate targets, and international agreements (Niklaß et al., 2019; Fuglestvedt et al., 2010). 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 (Dodd et al., 2020). While alternative metrics, such as ATR, provide a more nuanced representation of short-lived effects and contrails (Marais et al., 2008; Dallara et al., 2011; Dahlmann et al., 2016), 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.

3. Method

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 (International Organization for Standardisation, 2020a,b) 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 Fig. 1):

(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 Available Seat Kilometre (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 Passenger (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

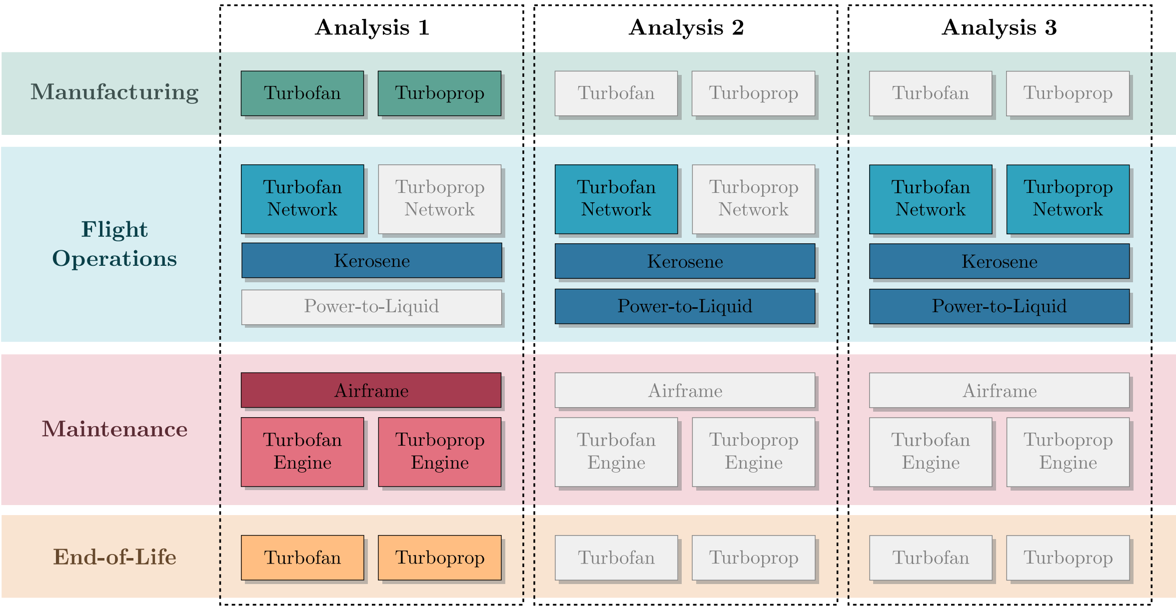


Fig. 1. Graphical overview of the three analyses performed. The coloured boxes indicate what is included within the system boundaries of each analysis.

Europe. The impact assessment was performed according to the method of Fazio et al. (2018) 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.

3.1.1. *Analysis 1: Comparison of turbofan and turboprop aircraft*

Both aircraft designs were developed as part of DLR's Exploration of Electric Aircraft Concepts and Technologies (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 International Civil Aviation Organization (2019). The Operating Empty Weights (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 Fig. 2). The material and mass distributions of the aircraft designs are primarily based on Atanasov et al. (2023). 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.

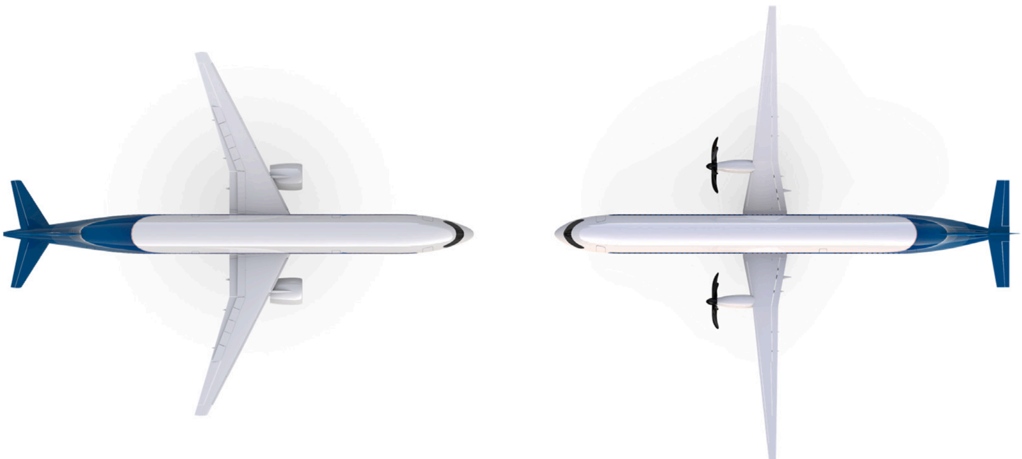


Fig. 2. Conventional turbofan (left) and turboprop (right) aircraft developed for the DLR-internal EXACT project (source: DLR, internal documentation).

The propulsion systems (turboprop engine vs. 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 and is 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 nautical miles (nm) and operate under the same flight schedule, ensuring comparability. However, the superior fuel efficiency of turboprops at lower altitudes (Babikian et al., 2002) 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 (Atanasov et al., 2023).

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 (Oestreicher et al., 2024). 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 Life Limited Parts (LLPs)). The two aircraft maintenance schedules are developed according to Rahn et al. (2024) and Oestreicher et al. (2024). Table 1 gives an overview of the maintenance checks for both aircraft, including their durations and intervals, which are given in Flight Cycles (FCs) and Flight Hours (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.

3.1.2. Analysis 2: Comparison of kerosene and PtL

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 (Silberhorn et al., 2022), 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. (2014) was chosen. Wind power was selected as the renewable energy source.

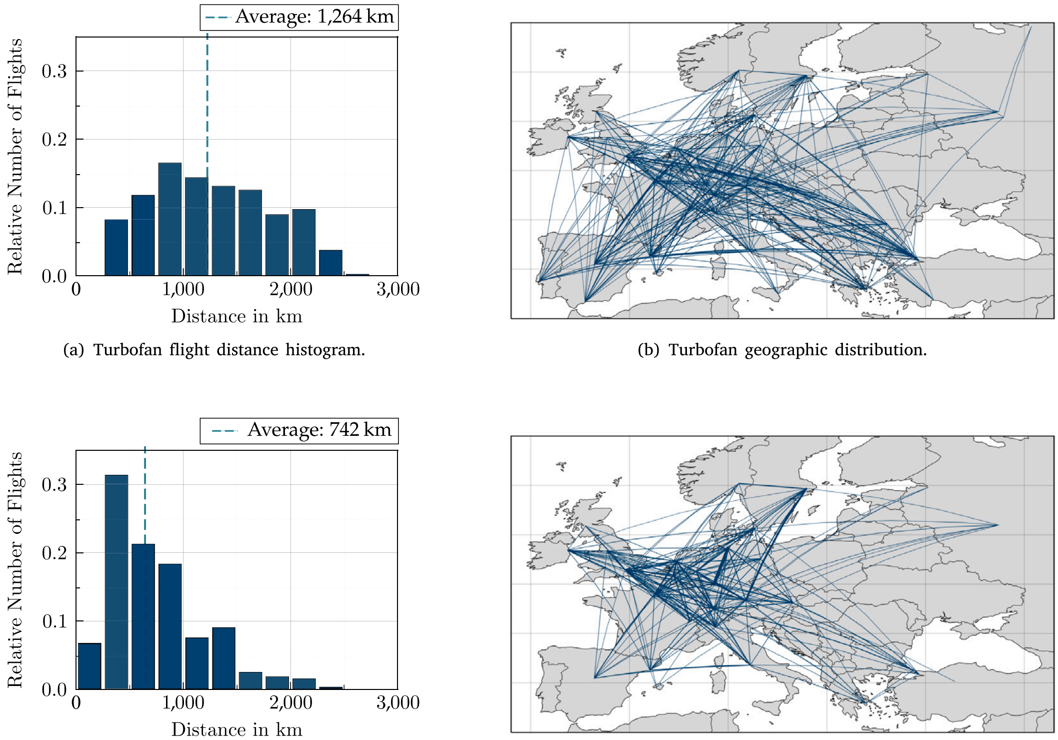
3.1.3. Analysis 3: Comparison of flight schedules

The two aircraft concepts are designed on the basis of the same top-level aircraft requirements (as specified by Atanasov et al. (2023)), 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. However, 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 determines on which routes it is preferable for the airline to operate both aircraft, considering their respective properties

Table 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 (Ackert, 2012; Aircraft Commerce, 2001, 2007, 2021).

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



(a) Turbofan flight distance histogram.

(b) Turbofan geographic distribution.

(c) Turboprop flight distance histogram.

(d) Turboprop geographic distribution.

Fig. 3. Flight distance histograms and geographical distributions of the two flight schedules.

(e.g., range, speed, and operating cost) and the airlines' operational flight planning constraints (Kühlen et al., 2022). The sequences of representative routes are then aggregated into the two flight schedules. 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. Fig. 3 shows the flight distance histograms and the geographical distributions of the two flight schedules.

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 (Wernet et al., 2016). The foreground inventory for the aircraft was derived from Rahn et al. (2022) 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. (2025) 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% (Chamorro et al., 2019). The energy for casting, forging, and machining of the materials is taken from literature with buy-to-fly ratios of 2.5 for casting (Salonitis et al., 2016) and 2.4 for forging (Cha et al., 2011). 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. (2024) and adapted for the two engine types. Information on engine maintenance was collected and combined from various sources (Aircraft Commerce, 2007, 2021; Oestreicher et al., 2024). 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 (Allacker et al., 2017). 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. (2014). The energy for green hydrogen production is generated from wind power in Germany, which is evenly split between 50% onshore and 50% offshore contributions (Jacobson et al., 2017). 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 Contrail-Induced Cloudiness (CIC) across different atmospheric regions (Fichter, 2009). Interested readers are referred to Dahlmann et al. (2021) for more information. Because the trajectory is simulation in discrete range steps of 100 nm (approx. 185 km) (Linke et al., 2020), 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. (2016)) 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.

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 Life Cycle Cash Flow Environment (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 (Banks, 2010). 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 (Wohlgemuth et al., 2006). 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 (Rahn et al., 2022; Thiede et al., 2013). 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. (2021). The framework can be further extended to include environmental assessment, as detailed in Rahn et al. (2022) and Rahn et al. (2024). An independent LCA based on the generated inventory explained in Section 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 (Linke et al., 2017). The climate impact of in-flight emissions is then assessed with the climate response model AirClim. As described by Dahlmann et al. (2016) and Grewe and Stenke (2008), 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 (Stenke et al., 2008). 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 and Kärcher (2009, 2011).

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 climate change impact category. The GWP result for each flight is attached to the respective flight event during the LYFE simulation and interpreted after post-processing. Fig. 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. (2020).

4. Results

The result 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 more 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 that adapted flight routes can have on the environmental impact. An overview of the results for all impact categories and scenarios can be found in the supplementary materials.

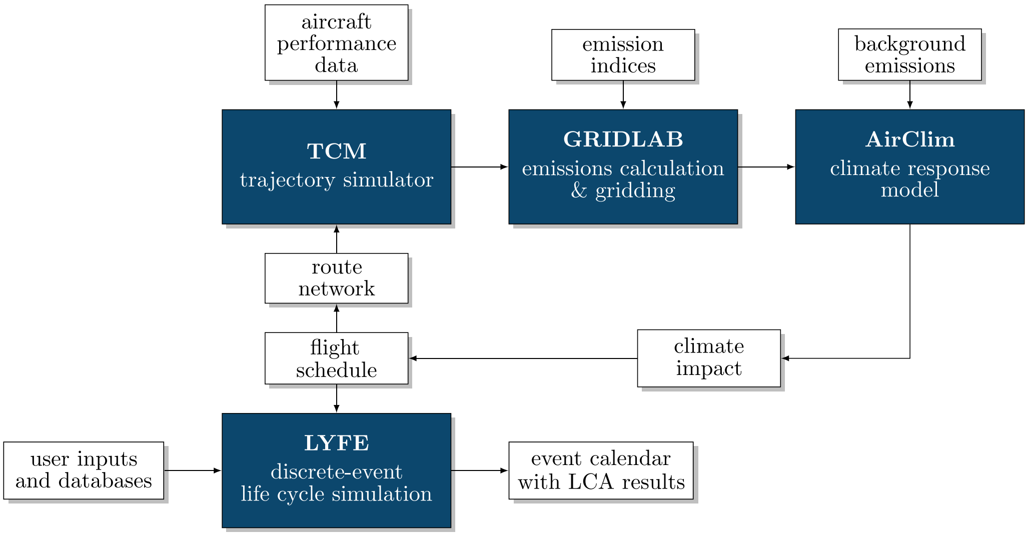


Fig. 4. Schematic overview of the combined tools LYFE, TCM, GRIDLAB, and AirClim, including inputs and outputs.

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 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).

The results for the impact category of climate change with the indicator GWP are presented in Table 3. All the results are provided in the functional unit per lifetime and per ASK. The results of the climate impact evaluation during flight can be calculated only with the metric GWP.

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 Fig. 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, which can be attributed, among

Table 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%

Table 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 both as totals over the entire life cycle and per ASK.

Life Cycle Phase	GWP [tCO_2-eq./lifetime]		GWP/ASK [gCO_2-eq./km]	
	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

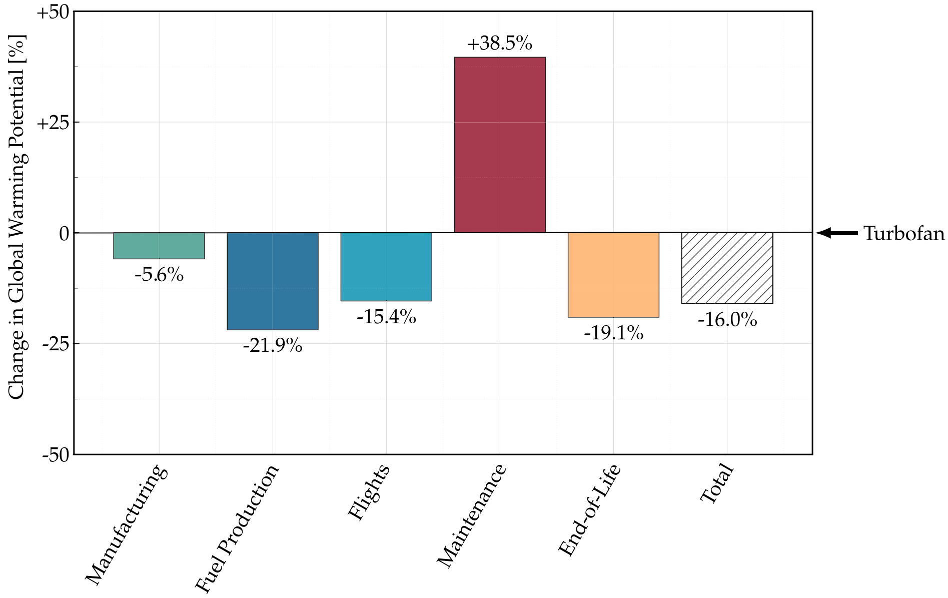


Fig. 5. Changes in the GWP of the turboprop aircraft compared with that of the turbofan aircraft for each life cycle phase when powered with kerosene.

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 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. Fig. 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 red) 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 (Rahn et al., 2024). The variations between the turbofan and turboprop engines can be seen in the engine maintenance bars (light red). 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).

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 0.13%, whereas for turboprop aircraft, it is 0.22%. Nevertheless, efficient maintenance and overhaul practices are significant means of reducing the environmental impacts of flight operations, for example, by introducing regular engine washing (Rahn et al., 2021). The LCA results associated with maintenance thus demonstrate that, despite its comparatively minor implications, significant positive effects can be achieved through maintenance.

Table 4
Reduction in GWP for different propeller replacement intervals during engine overhauls.

Propeller Replacement Interval	Total Maintenance GWP [kgCO_2-eq.]	GWP Reduction [%]
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

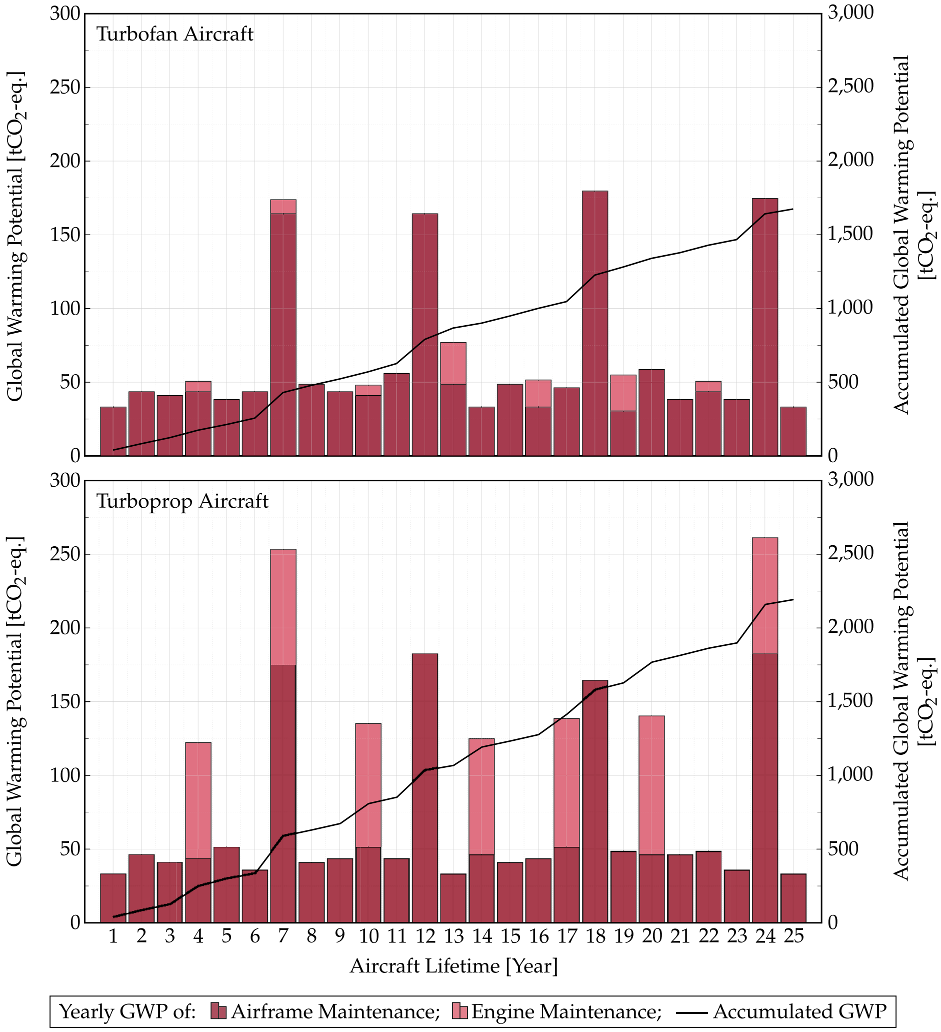


Fig. 6. Yearly distribution of the GWP of the airframe and engine maintenance (primary axis) and the accumulative GWP of total maintenance over the turbofan (top) and turboprop (bottom) aircraft lifetimes (secondary axis).

4.2. Comparison of kerosene and PtL

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 (Notten et al., 2021). Fig. 7 illustrates the distribution of the clustered flights in GWP per ASK 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 (1^{st} and 3^{rd} quartiles) are provided. A long violin plot indicates that the data points are distributed over a wide range with a few outliers.

PtL has only approximately half the impact of kerosene in terms of CO_2-eq. The production of PtL has a smaller impact on the climate change category (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. (2021). 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

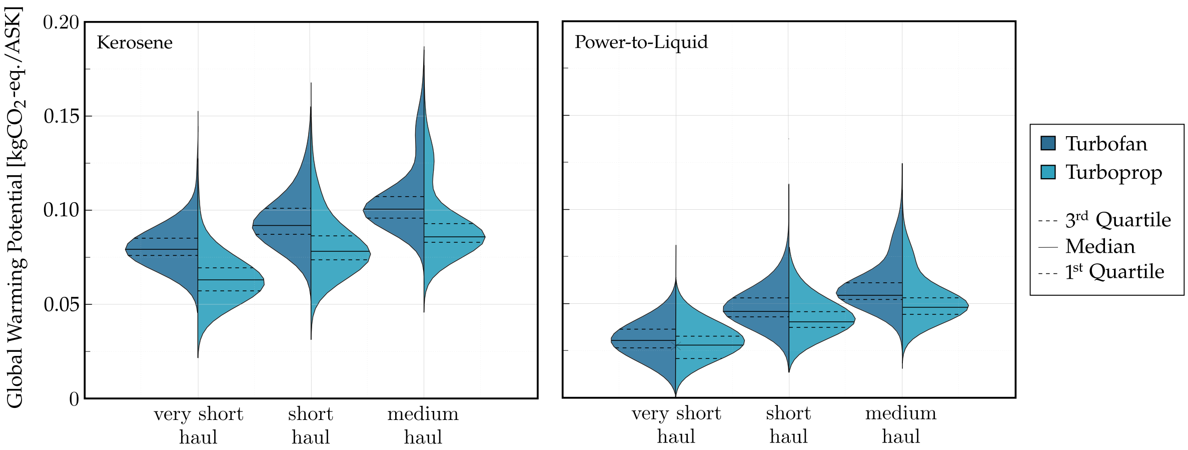


Fig. 7. Distribution of the GWP results for the flight distance categories of very short-haul (up to 800 km), short-haul (800-1,500 km), and medium-haul (1,500-4,000 km) flights for kerosene (left) and PtL (right), including a comparison between turbofan and turboprop aircraft. The median and quartiles are shown in the violin plots to indicate the spread of the data.

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. (2021).

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. Fig. 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.

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 climate change 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. (2014)), 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. 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.

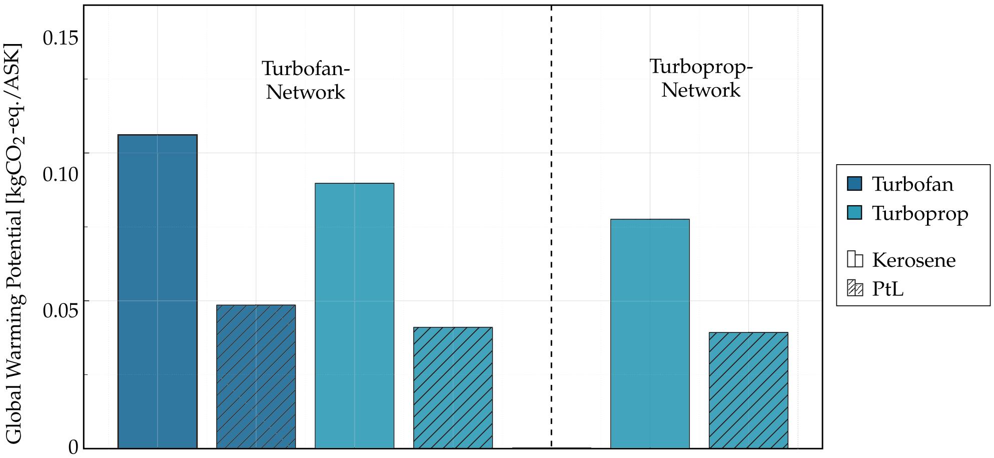


Fig. 8. Comparison of the GWP per ASK for turbofan and turboprop aircraft, assuming a flight network adapted specifically for the turboprop. All the results are given for both kerosene and PtL.

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. (2025), which also highlights the ecological benefits of PtL over conventional kerosene fuels. Moreover, the results of our study contradict the correlation observed in Cox (2018), Rupcic et al. (2023), or Egelhofer et al. (2008), 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.

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 climate change 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. (2018), 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.

CRediT authorship contribution statement

Antonia Rahn: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Katrin Dahlmann:** Writing – review & editing, Software, Methodology, Data curation. **Florian Linke:** Writing – review & editing, Software, Methodology, Data curation. **Markus Kühlen:** Writing – review & editing, Visualization, Software, Methodology, Data curation. **Benjamin Sprecher:** Writing – review & editing, Supervision. **Clemens Dransfeld:** Writing – review & editing. **Gerko Wende:** Funding acquisition.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their gratitude to Dr. Kai Wicke for his support and proofreading of this manuscript.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.trd.2025.104646.

Data availability

Data is shared in the supplementary materials.

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