SUSTAINABLE ENGINE MAINTENANCE: EVALUATING THE ECOLOGICAL IMPACT OF LIFE LIMITED PART REPLACEMENT

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Abstract

While the aviation industry has historically focused on in-flight emissions, the environmental impact of engine maintenance has often been underestimated. However, maintenance has a significant impact on the subsequent performance of the engine and therefore on the environmental impact during operation. This study examines the ecological implications of engine maintenance, with a particular focus on Life Limited Parts (LLPs), which require frequent replacement. A Life Cycle Assessment (LCA) was employed to analyze the environmental consequences of specific LLP replacement workscopes for IAE V2500 engines. This included material exchanges, task execution and the final testing of the engine. The findings of this study indicate that, in addition to fuel combustion during testing, the replacement of LLPs contributes substantially to the ecological footprint. Furthermore, the energy consumed during the disassembly and assembly of the engine is a notable factor, which highlights the necessity of considering sustainability in engine maintenance practices in a comprehensive manner.

Keywords: Life Cycle Assessment, Engine Maintenance, LLP Replacement

1. Introduction

The aviation industry is currently at a critical point in its journey towards sustainability, driven by technological advancements and increasing environmental regulations [1, 2]. As the sector seeks to reduce its ecological footprint, it is becoming increasingly important to understand the environmental impacts across all aspects of aircraft operation and maintenance. One critical area in this regard is engine maintenance. In order to achieve meaningful progress, it is crucial to evaluate the environmental effects throughout the entire life cycle of an engine, from raw material extraction and manufacturing to operation, maintenance, and end-of-life.

In literature, little attention has been paid to conventional engines as a comprehensive system. Studies often provide only a superficial examination of the engine in terms of its total weight or total cost within the context of broader discussions on aircraft systems and their operation [3–5]. These studies do not adequately represent the complex machining and repair processes of engine parts, or the usage of highly specialized and unique nickel and titanium superalloys. Conversely, several other studies offer a detailed examination of individual components, [6–10], where the machining and production processes of specific parts are considered.

Vinodh and Veeramanikandan [6] conducted a study analyzing the manufacturing processes of a turbine blade made of a nickel-base alloy. Their findings highlighted that laser machining and raw material extraction were the primary contributors to the environmental impact of a turbine blade. A study by Leonard [7] focused on the production, manufacturing and end-of-life scenarios of metal and composite materials in the engine's cold sections. In a related study, Rolinck et al. [8] applied a blockchain-based data management concept to the repair process of a turbine blade for LCA, although they were limited to using dummy data. In addition, Bergs et al. [9] and Fricke et al. [10, 11] examined the manufacturing processes of High Pressure Turbine (HPT) blisks, considering the extraction of raw materials as well as different machining parameters. The study by Bergs et al. [9] concluded that the manufacturing phase, in addition to the operational phase of an aircraft component, has a significant environmental impact.

In the majority of these studies, the aspect of maintenance is rarely considered, receiving only superficial attention in studies of future engine concepts [12], the overall aircraft maintenance process [13] or for specific maintenance tasks [14] rather than for a complete engine shop visit. Keivanpour et al. [15] proposed a framework for performing an ecological assessment of engine maintenance, but ultimately did not have sufficient data available. Previous research has often considered the ecological impact of maintenance in the aviation sector to be negligible for further investigation [16]. However, a critical insight from the literature is that although 99% of emissions originate from engine use, degradation accounts for a significant 3.6% to 6.4% of total emissions, as highlighted by Jakovljevic [17]. Therefore, even a slight reduction in emissions due to degradation, which refers to the gradual breakdown or deterioration of engine components over time, could have a significant environmental impact and underscores the importance of understanding the impacts of engine maintenance. However, recent studies conducted by Barke et al. [12] and Rahn et al. [13] have shown that, in particular, the replacement of components during maintenance has a notable ecological impact.

During the maintenance of an engine, one specific task is performed on a regular basis, which ultimately necessitates the replacement of several specific components. This process is called LLP replacement. Since these LLPs consist of high-quality materials, it is assumed that their replacement will result in a significant ecological impact over all engine maintenance shop visits.

This research aims to address the existing research gap in environmental assessment of engine maintenance, with a particular focus on the replacement of so called LLPs. We conducted a detailed analysis of LLP replacement for a V2500 engine using a bottom-up approach. This included examining the disassembly and reassembly processes, the exchange of old parts with new ones, and engine testing. The replacement of LLPs represents a key aspect of engine maintenance and serves as an vital use case for this study due to its outstanding importance for flight safety, the defined maintenance protocols and its significant influence on general engine overhaul. The objective of this study is to comprehensively understand the environmental impacts associated with engine maintenance and establish a foundation for future research in this area.

The paper is structured as follows: Firstly, we provide a brief description of engine maintenance in general and of the Life Cycle Assessment (LCA) methodology. We then apply the LCA methodology to evaluate the environmental impact of each engine maintenance activity. Subsequently, the environmental impact of LLPs in general and over the entire service life of an engine, as well as the distribution of various tasks within engine maintenance, is presented. The conclusion summarizes the findings and recommends areas for further analysis in future studies, highlighting that the current assessment provides important insights.

2. Fundamentals

The intention of this Chapter is to introduce readers that are unfamiliar with engine maintenance (Chapter 2.1) and LCA (Chapter 2.2), to general shop maintenance processes as well as the methodology of ecological assessment.

2.1 Maintenance of aircraft engines

The main objective of this chapter is to highlight the fundamental elements of engine maintenance and the key factors that influence both the maintenance procedures and their environmental impacts. Before delving into the specifics of engine maintenance and its impact on the environment, it is crucial to understand the innovative concept of modular engine design. This approach revolutionizes traditional engine manufacturing by dividing the engine into interchangeable modules. Figure 1 shows exemplary the modules of an IAE V2500 engine, each consisting of several sub-modules. By applying this modular architecture, manufacturers can optimize maintenance processes, increase efficiency, and minimize downtime during repairs. These modules include the fan, Low Pressure Compressor (LPC), High Pressure Compressor (HPC), combuster, HPT and Low Pressure Turbine (LPT). Each

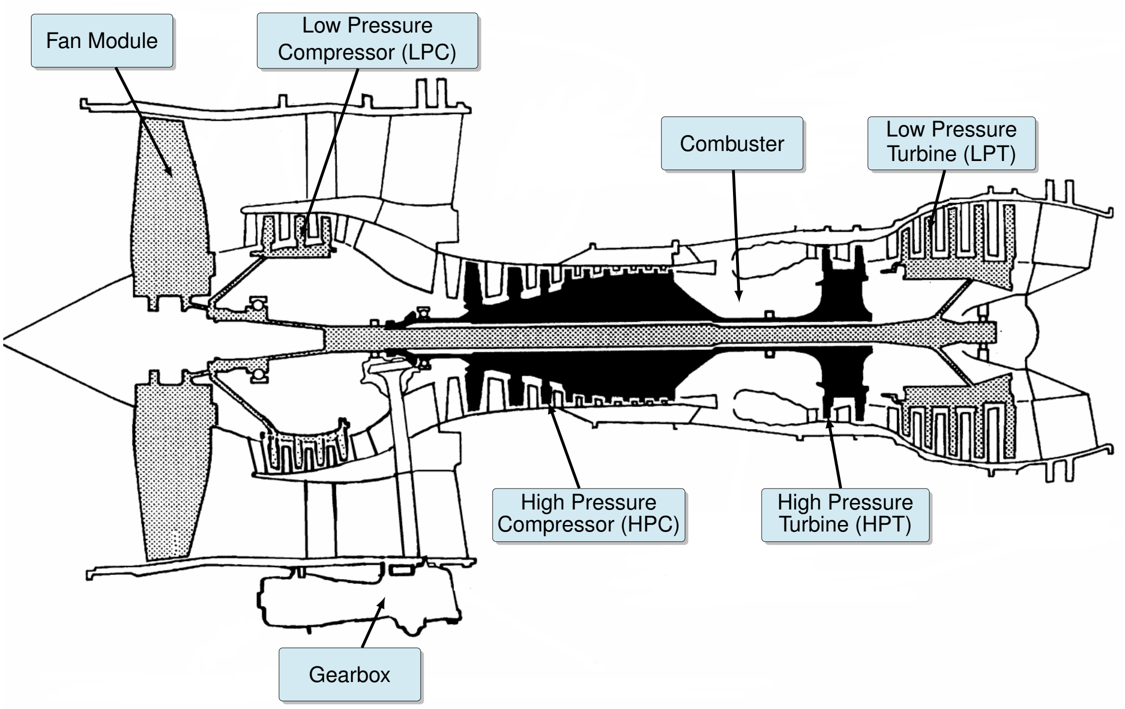


Figure 1 – Main modules of a V2500 engine, developed from [20].

module plays a specific role in the engine's operation, such as air intake, compression, combustion, and energy extraction. These modules work together seamlessly to power the engine and generate thrust for aircraft propulsion.

Generally, the maintenance workscope for each engine shop visit is based on specific criteria aimed at ensuring safe operation until the next shop visit [18]. Engines are removed from the wing for several reasons. Besides a degraded Exhaust Gas Temperature (EGT) margin or critical hardware condition found during line inspections, the replacement of Life Limited Parts is one of the main reasons to send an engine to a dedicated Maintenance, Repair and Overhaul (MRO) provider [19, 21, 22]. LLPs are crucial components for safety and have to be regularly replaced to ensure optimal performance and reduce the risk of failure. These have a number of permitted Flight Cycles (FCs) that must not be exceeded and can be parts such as discs, seals or shafts [18, 19].

The maintenance process, illustrated in Figure 2, involves disassembling the engine into modules, then further into sub-modules and individual parts. In addition to LLPs, which have a defined lifespan, all other parts need to be inspected. Depending on their condition, these parts can be reused or repaired. If their condition exceeds the limits set by the engine manual, these so called scrap parts must be replaced with new ones. After maintenance the engine is reassembled and tested.

The processes of part replacement, part repair and testing are likely to have a significant ecological impact. This impact arises not only from the use of high-quality materials such as nickel, titanium, and cobalt alloys, which often need replacement, but also from the energy-intensive nature of repair processes like chemical cleaning, welding, heat treatment or coating application. Furthermore, during the engine testing phase, a considerable amount of kerosene is consumed in order to simulate operational conditions and verify the engine's performance and safety. The burning of kerosene during these tests further contributes to the ecological impact.

2.2 Life Cycle Assessment

Within this study, the well-established LCA method of DIN EN ISO 14040 [23] and DIN EN 14044 [24] is employed. Generally, LCA is a valuable tool for comprehensively analyzing the environmental performance of a product throughout its entire life cycle, encompassing the stages from initial conceptualization through production and operations to its eventual end-of-life. LCA enables the comparison of environmental impacts of different products or processes that serve the same function. It is also effective for identifying process hot spots [25].

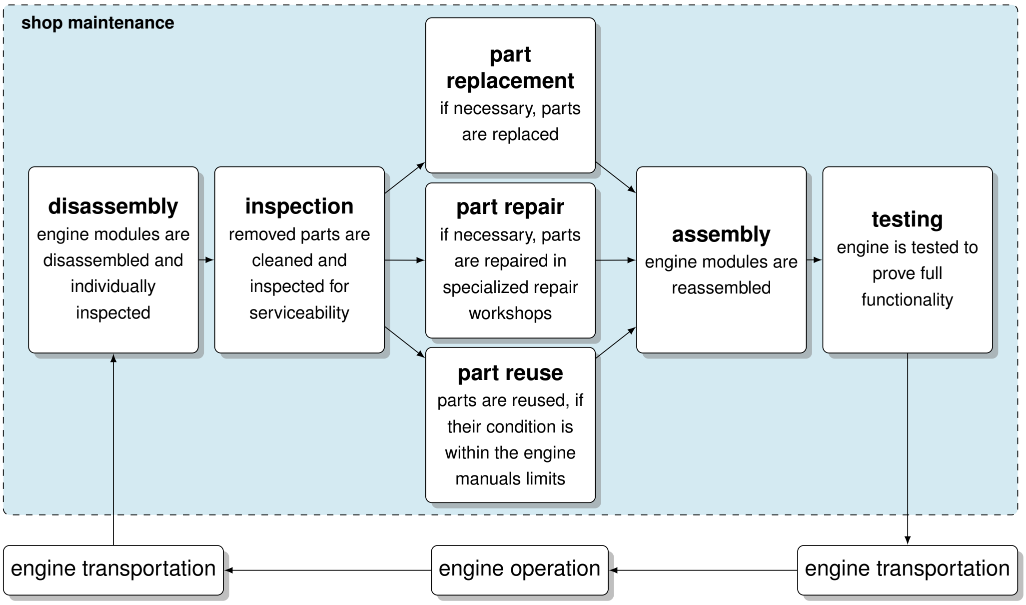


Figure 2 – The process of engine maintenance.

The LCA involves four distinct steps, as outlined below and depicted in Figure 3: Initially, during the goal and scope phase, the intention and the methodology of the study are defined, analysis goals are set, and system boundaries are established in order to focus on relevant environmental impacts and activities. This step is crucial for ensuring the comprehensive collection of all important information, which is carried out in the second step, the inventory generation (Life Cycle Inventory (LCI)). The LCI includes information about material resources and energy flows, as well as outputs, such as expected waste and emissions. The subsequent step involves assessing these inputs and outputs across various environmental impact categories, a process known as the Life Cycle Impact Assessment (LCIA). Finally, the fourth step focusses on interpreting and discussing the results obtained, ensuring they align with the initially defined goals and scope [23, 24]. The LCA calculation in this study was carried out with the open-source Python-based brightway2 framework [26] and the ecoinvent 3.9.1. database [27]. Furthermore, the Environmental Footprint (EF) 3.1 method [28] was employed for the LCIA.

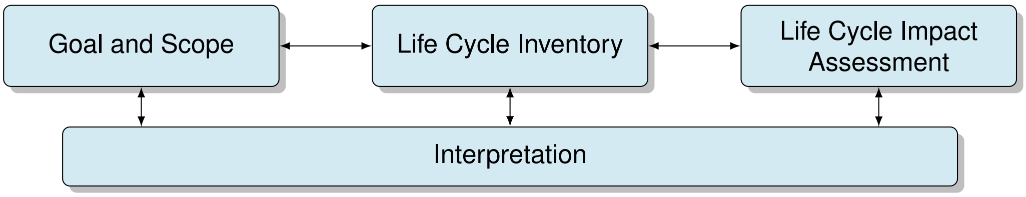


Figure 3 – The four phases of LCA.

3. Goal and Scope Definition

In this chapter, we elaborate on the essential steps of the goal and scope definition and define the use case, functional unit, and system boundaries.

Use Case In this study, the aim is to assess the environmental impacts of maintaining a V2500 aircraft engine. An LCA will be conducted focusing on a case study involving a shop visit for the replacement of LLPs. According to the V2500 engine manual [29], a total of 25 LLPs need to be replaced every 20,000 FC. Compared to other maintenance activities, the procedures for replacing LLPs are well-structured and require a comprehensive engine disassembly. In addition to disassembly and final assembly, specific inspection and cleaning tasks are performed, along with the actual LLP replacement as well as an engine test at the end of every shop visit. Figure 4 illustrates the general

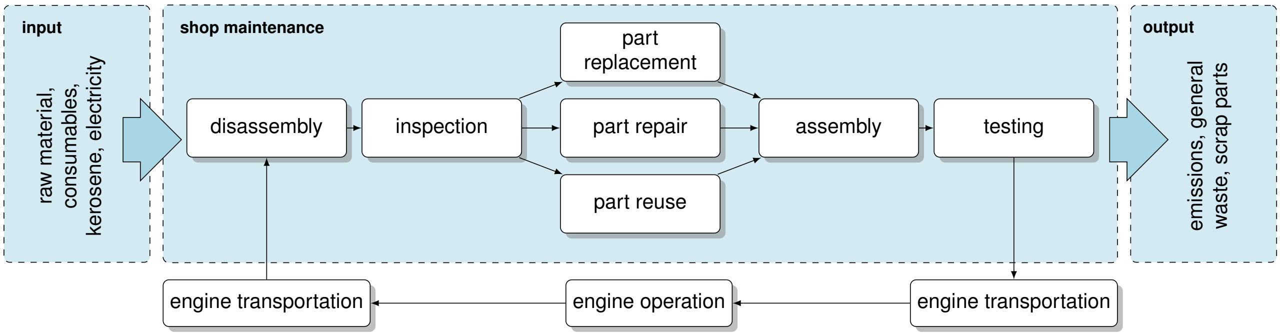


Figure 4 – The process of engine maintenance in context of LCA with all important in- and output data. The focus of this study is on the process parts outlined in dark blue.

steps of engine maintenance. In this paper, the focus lays on the highlighted steps: disassembly, part replacement, assembly and testing. Additionally, we analyzed not only LLPs but also other components that must be replaced as part of an LLP replacement workscope, such as vanes and blades. The data of the so called scrap parts are derived from data provided by MTU Maintenance GmbH based on 25 V2500 engines.

Functional Unit For this study, the functional unit was defined as per LLP replacement. Subsequently, the results were further analyzed per Flight Hour (FH), enabling comparison of LCA results across different operating scenarios.

System Boundaries The system boundaries are shown in Figure 4, which describes the engine maintenance process. The highlighted processes (disassembly, part replacement, assembly and testing) constitute the scope of this study. Additionally, the main assumptions and limitations in this study are listed as follows:

General Assumptions

- the activities are mainly carried out in Europe
- the ecological impact of the engine due to the original production is not considered

Engine Parts

- the calculations for each part are based on the main material
- coatings on specific parts are not considered
- the usage of recycled material or used parts is not considered
- no consideration of disposal, recycling or other end-of-life scenarios of scrap parts
- part machining was not considered
- impacts due to part transportation ordered from original manufacturer are not considered

Task-related Assumptions

- the emissions of the engine test bed are based on industry data
- impacts related to maintenance staff (e.g. commuting, personal waste) are not considered
- tasks related to main inspection and repair processes are not considered
- logistic areas (warehouse, storage) are not considered
- transportation of the engine to the maintenance shop is not considered

4. Inventory Generation

The methodology of this study is based on a detailed examination of the required maintenance tasks, as specified in the V2500 engine manual [29]. As a result, all planned and recorded tasks of a standard LLP replacement workscope of one specific engine were classified into distinct task types, including disassembly, part replacement, assembly and testing. Additionally, data from 25 aircraft (detailed in Table 1) were used to analyze a total of 25 LLPs and 93 other components that require regular replacement. The distribution of these components across the various engine modules is shown in Figure 5. It is noted that LLPs account for 91% of the material weight needing replacement during an LLP replacement workscope, while scrap parts contribute only 9%.
The total ecological impact of an LLP replacement is determined by the following expression:

$$E = \sum_{i=1}^{5} E_i \tag{1}$$

where,

- E_1 - the ecological impact of LLP production
- E_2 - the ecological impact of scrap part replacement
- E_3 - the ecological impact of engine disassembly
- E_4 - the ecological impact of engine assembly
- E_5 - the ecological impact of engine testing

Table 1 – Overview data of the analyzed engines.

Characteristic	Data
Engine Type	V2527A5
Average Cycle Since New (CSN)	19,490 FC
Average Cycle Since Last Shop Visit (CSLSV)	19,490 FC
Average Time Since New (TSN)	31,230 FH
Average Flight Ratio (FH/FC)	1.6
No. of Shop Visit	1st
No. of LLP Replacement	1st
Operation Environment	moderate (e.g. Europe)
Thrust Rating	24,800 lbs

LCI of LLP production - E_1 The materials and weights of the LLPs were extracted from MTU systems and included in the inventory accordingly. This information is presented in Table 2, which lists the engine module, the materials, and the weighting percentage distribution of the alloys. The LCA calculation was performed using the material as specified in the engine manual [29] and from the literature. The overall weight of LLPs replaced accounts for 21% of the whole engine weight. To refine the analysis further, an additional value for alloy fusion was calculated based on the melting temperatures of the base material [30, 31] for each alloy used in the LLPs replacement and added to the inventory.

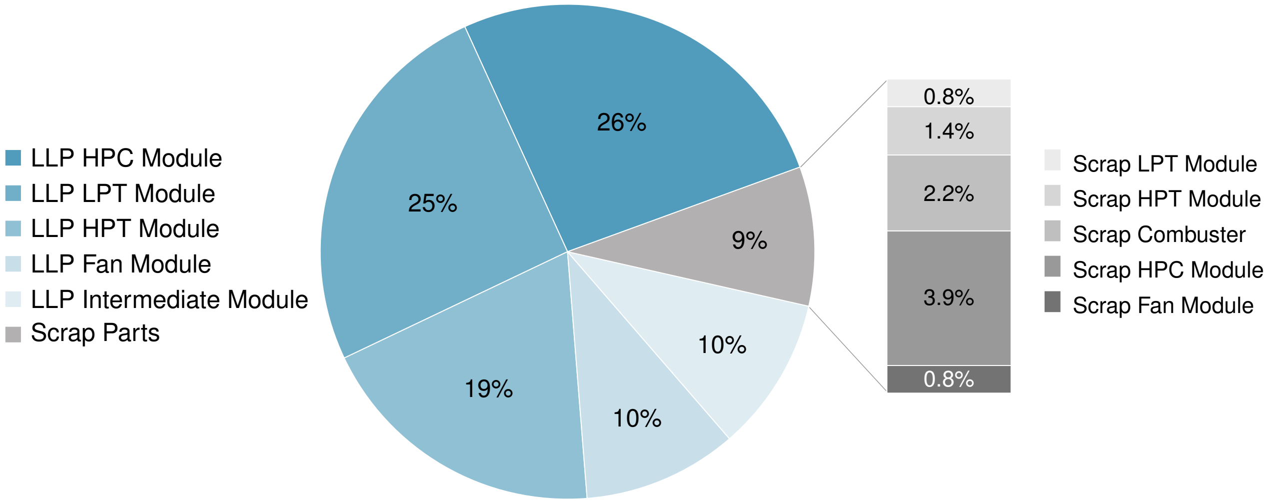


Figure 5 – Weight distribution of replaced parts to the modules.

Table 2 – LCI of replaced materials for LLPs.

Module	Material	Weight Distribution
Fan module	titanium alloy	11.4 %
LPC module	titanium alloy	8.5 %
	steel	2.7 %
HPC module	titanium alloy	11.4 %
	nickel alloy	17.3 %
HPT module	nickel alloy	21.4 %
LPT module	nickel alloy	16.9 %
	steel	10.4 %

LCI of scrap part replacement - E_2 Data from over 90 different components were analyzed. The scrap rate of each component was calculated and multiplied by the component weight to determine the average amount of material that needs to be replaced. Table 3 displays the weight and material distribution among the modules for the components designated for substitution. On average, materials equivalent to about 2.1% of the engine weight are set for renewal within a typical LLP replacement workscope. Similar to the LLPs an additional value for alloy fusion was calculated and included in the analysis. The LCA calculation was performed using the alloy as specified in the engine manual [29] and from the literature.

For each analyzed component, the processes of raw material extraction and alloy production were considered, as illustrated in Figure 6. However, due to the lack of data, no information on the production of the components and their transportation to the maintenance service provider was included.

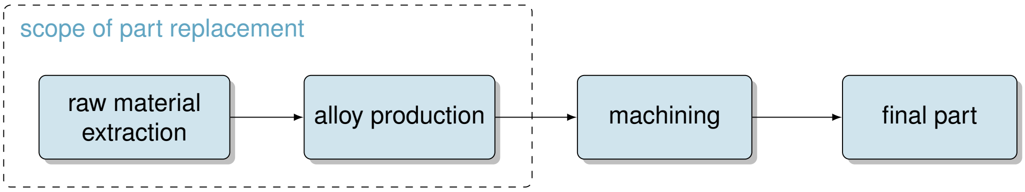


Figure 6 – The scope of ecological estimations for LLPs and scrap part replacement.

Table 3 – LCI of replaced materials for scrap parts.

Module	Material	Weight Distribution
Fan module	titanium alloy	8.6 %
LPC module	titanium alloy	0.2 %
HPC module	titanium alloy	27.2 %
	steel	15.3 %
	cobalt alloy	0.04 %
Combuster	titanium alloy	22.4 %
	cobalt alloy	2.1 %
HPT module	nickel alloy	12.5 %
	cobalt alloy	2.9 %
LPT module	nickel alloy	8.7 %

LCI of general tasks - E_3, E_4, E_5 The inventory includes information on tasks related to disassembly, assembly, and testing. According to the literature [13], consumables such as cleaning agents (e.g. acetone) and lubrication oil during disassembly and assembly contribute less than one percent to the maintenance-related ecological impact. Therefore, this data was not collected and thus excluded from the present study. The planned working hours of each task category were aggregated and allocated to the activities presented in Table 4. This allocation took into account the different modules as described in Chapter 2.1 and the relevant tasks related to these categories from Figure 4. The part replacement process is assumed to be included in the logistics process task category, as it encompasses all necessary organizational tasks for maintaining an engine and providing the required materials and tools. The subsequent analysis summarizes the various task categories within the context of engine disassembly, which includes incoming inspection and half of the time required for logistics, such as material planning and functional marshalling. Similarly, engine assembly, which also includes the remaining half of logistics. This is done for the sake of visualisation.

Table 4 – Share of man-hours across the engine modules and task categories.

Task Category	Engine	Fan	LPC	HPC	Combuster	HPT	LPT	Gearbox	sum
incoming inspection	0.5%	-	-	-	-	-	-	-	0.5%
engine disassembly (tear down)	9.1%	0.3%	6.9%	5.2%	0.3%	1.0%	2.9%	2.9%	28.6%
logistics & material planning	2.5%	0.6%	1.3%	1.5%	0.6%	1.4%	1.7%	0.8%	10.4%
engine assembly (build up)	17.9%	1.0%	9.5%	10.4%	1.5%	1.9%	4.1%	6.8%	53,1%
engine test	7.4%	-	-	-	-	-	-	-	7.4%
sum of all tasks	37.4 %	1.9%	17.7%	17.1%	2.4%	4.3%	8.7%	10.5%	100%

Table 4 shows that engine assembly is the most labour-intensive tasks, accounting for over 50% of the total man-hours. This includes significant shares in general engine related tasks, such as the reassembly of systems, but also with high shares in the LPC (9.5%), the HPC (10.4%) and the gearbox (6.8%) modules. Engine disassembly accounts for more than 28% of the total man-hours, with notable contributions from the engine system disassembly (9.1%) as well as the LPC (6.9%) and the HPC (5.2%). Logistics and material planning make up 10.4% of the total man-hours, with smaller yet consistent contributions across all modules. The data indicates that disassembly and assembly tasks are the most labour-intensive activities in engine maintenance.

The data shown in Table 4 is essential for calculating the environmental impact of each task, as this is determined by the shop operation. The planned man-hours are employed to calculate the consumed energy for electricity (e.g. lighting, tool usage) and heating of the building. Further, the determination of the electricity consumption during disassembly and assembly was conducted by measuring the area utilized for these tasks. The assumed values are presented in Table 5. For a V2500 engine, an area of 70 m^2 was considered, including a fractional amount for logistical activities. Subsequently, the electricity consumption of the entire workshop area was calculated. The energy mix utilized for the analysis is based on the percentage distribution presented in MTU's environmental statement [32] and the data from the German Federal Environment Agency [33] on electricity generation. The average consumption of kerosene and electricity during a standard V2500 test was calculated using data from the year 2023.

Table 5 – LCI of general tasks during LLP replacement.

Activity	Influencing Factor	Quantity
shop operation	electricity	4500 kWh
on site transportation	diesel	12 kg
engine testing	kerosene	3100 l
engine testing	electricity	770 kWh

5. Life Cycle Impact Assessment

This section presents the results of the LCIA. The findings of the LCIA calculations of LLP and scrap part replacement as well as general maintenance tasks and the engine testing are presented in Chapter 5.1, while Chapter 5.2 contains a sensitivity analysis of the calculated results.

5.1 Ecological Implications of LLP Replacement

With the collected inventory, the LCIA was performed using the EF 3.1 method. This method addresses 15 environmental impact categories, which include implications for climate change, ecosystem quality and resource use [34]. An overview of the LCIA results for these impact categories, corresponding to each activity involved in the LLP replacement, is presented in Table 6.

The activity associated with material replacement for LLPs has the greatest impact across a number of categories, with notable contributions in Acidification (388 mol H+ eq.), Water Use (23,050 kg world eq. deprived), and Minerals and Metals (1.29 kg Sb eq.). The testing phase is another significant contributor, particularly in terms of Climate Change (10,423 kg CO_2 eq.) and Energy Carriers (140,445 MJ). In contrast, disassembly and assembly tasks have relatively lower impacts compared to materials and testing.

For further analysis, this study will focus on three impact categories, namely Climate Change (expressed in kg CO_2 eq.), Freshwater Ecotoxicity (with the unit CTUe) and Mineral and Metals (expressed in kg Sb eq.) [34], due to their broad bandwidth and variety.

In detail, Table 7 shows, that the greatest contributor to Climate Change, represented by the indicator Global Warming Potential (GWP), is the LLP replacement, followed by the engine testing, which involves burning kerosene. This is similar within the other two impact categories - Freshwater Ecotoxicity and Mineral and Metals - where the replacement of LLPs has the highest share, primarily due to the extraction and production of highly alloyed materials. The data indicates that, although to a lesser extent, the disassembly and assembly processes have a measurable impact on Climate Change. In contrast, the impact of disassembly and assembly on Freshwater Ecotoxicity and Mineral and Metals is negligible.

Table 6 – The environmental impact of specific tasks during an LLP replacement workscope.

Activity	**Climate Change** *kg CO_2 eq.*	**Acidification** *mol H+ eq.*	**Freshwater Ecotoxicity** *CTUe*	**Freshwater Eutrophication** *kg P eq.*	**Marine Eutrophication** *kg N eq.*	**Terrestrial Eutrophication** *mol N eq.*	**Carcinogenic Effects** *CTUh*
materials LLP	13,737	388	159,902	0.92	18.0	192.4	8.101×10^{-5}
materials scrap parts	1.717	37	19,900	0.11	2.2	23.0	0.923×10^{-5}
disassembly	788	1	561	0.01	0.3	4.2	0.016×10^{-5}
assembly	1,331	2	856	0.01	0.6	7.0	0.027×10^{-5}
engine test	10,423	10	57,871	0.02	2.2	19.8	0.093×10^{-5}
full workscope	27,996	438	239,090	1.07	23.3	246.4	9.160×10^{-5}

Activity	**Ionising Radiation** *kBq U_{235} eq.*	**Ozone Layer Depletion** *kg CFC-11 eq.*	**Photochemical Ozone Creation** *kg NMVOC eq.*	**Respiratory Effects** *Disease Incidences*	**Water Use** *kg world eq. deprived*	**Energy Carriers** *MJ*	**Land Use** *m^2a*	**Mineral and Metals** *kg Sb eq.*
materials LLP	794	7.82×10^{-4}	83	14.79×10^{-4}	23,050	173,917	76,541	1.29
materials scrap parts	114	0.89×10^{-4}	9	1.66×10^{-4}	3,920	22,443	10,089	0.15
disassembly	3	0.31×10^{-4}	2	0.06×10^{-4}	75	11,588	4,114	0.00
assembly	5	0.53×10^{-4}	3	0.11×10^{-4}	127	19,397	6,951	0.00
engine test	25	2.34×10^{-4}	21	0.83×10^{-4}	210	140,445	9,046	0.00
full workscope	941	11.90×10^{-4}	118	17.45×10^{-4}	27,382	367,790	106,742	1.44

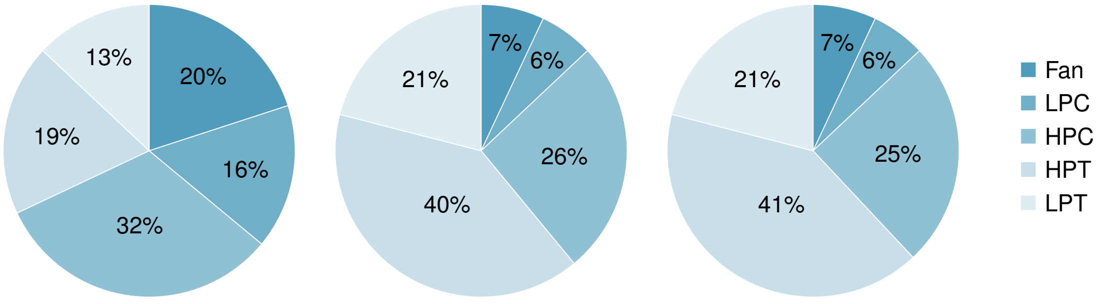
Table 7 – The environmental impact of an LLP replacement workscope per FH.

Activity	**Climate Change** per FH		**Freshwater Ecotoxicity** per FH		**Mineral and Metals** per FH	
	kg CO_2 eq.	%	*CTUe*	%	*kg Sb eq.*	%
materials LLPs	0.44	49.1	5.12	66.9	41.20×10^{-6}	89.1
materials scrap parts	0.05	6.1	0.64	8.3	4.89×10^{-6}	10.6
disassembly	0.03	2.8	0.02	0.2	0.03×10^{-6}	0.1
assembly	0.04	4.8	0.03	0.4	0.03×10^{-6}	0.4
engine test	0.33	37.2	1.85	24.2	0.07×10^{-6}	0.1
full workscope	0.89		7.66		46.22×10^{-6}	

In the context of Climate Change, the total impact of the full workscope amounts to more than 27,990 kg CO_2 eq, as illustrated in Table 6. For context, data published by Rahn et al. [35] indicates that an A320 type of aircraft emits approximately 17.7 kg CO_2 eq. per flown kilometer, which would total around 1,580 kilometers for the complete LLP replacement process.

The following paragraphs provide a detailed examination of the different activity types and their associated environmental impacts. First, the potential environmental impacts of LLPs and scrap parts are further investigated. This is followed by a detailed analysis of engine testing, as this activity has the highest impact in terms of GWP. Finally, the execution of general tasks is examined.

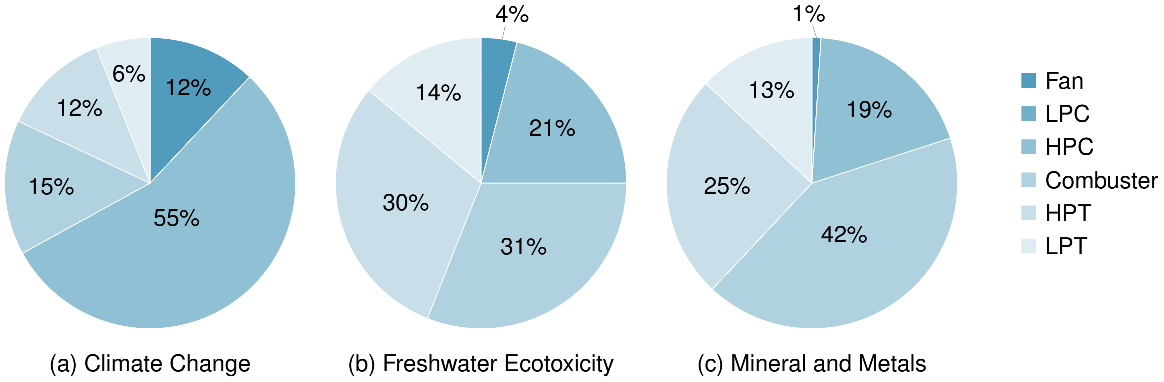
Life Limited Parts and Scrap Parts When focusing solely on LLP and scrap parts, it becomes clear that materials are becoming increasingly important, especially considering the prevalent use of high-alloyed superalloys in aviation. These materials, often selected for their superior strength and heat resistance, highlight the importance of assessing their environmental impacts. Figure 7 illustrates the environmental impacts associated with replacing LLPs and differentiates among the engine modules, namely Fan, LPC, HPC, HPT and LPT. The three impact categories of Climate Change, Freshwater Ecotoxicity and Mineral and Metals are analyzed as described above. It is notable that the Fan and HPC modules make considerable contributions to the Climate Change category, while the HPC and HPT module significantly impact the Freshwater Ecotoxicity category. In the Mineral and Metals category, the HPC and HPT modules are observed to have a notable impact.



(a) Climate Change (b) Freshwater Ecotoxicity (c) Mineral and Metals

Figure 7 – Share of LLP replacement over engine modules regarding the impact categories of (a) Climate Change, (b) Freshwater Ecotoxicity and (c) Mineral and Metals.

LLPs are critical components within an engine. However, the scrap parts described include a diverse range of items, such as vanes, blades and liner and ring segments. The quantity of these components in an engine increases in the hot sections of the engine and the complexity of the materials used, which is necessary to withstand higher temperatures. For example, within the HPC module, approximately 22.5 kg of primarily titanium and steel alloys are required for replacement. In contrast, the HPT module requires the replacement of 8.1 kg, comprising nickel and cobalt alloys.



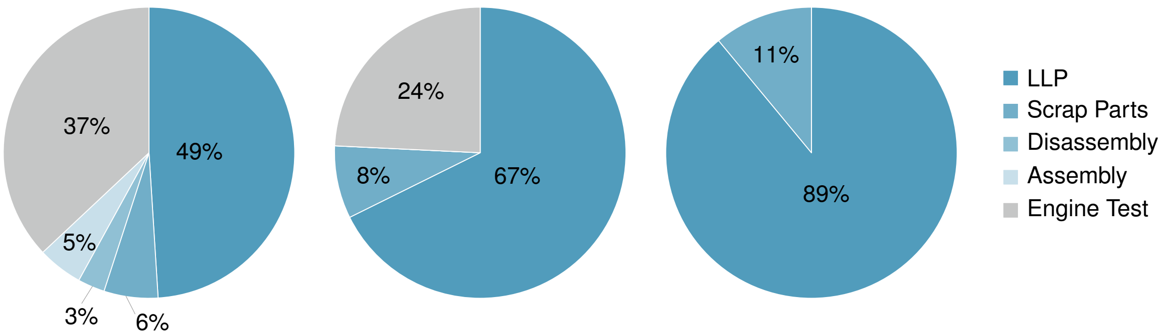
(a) Climate Change (b) Freshwater Ecotoxicity (c) Mineral and Metals

Figure 8 – Share of scrap replacement over engine modules regarding the impact categories of (a) Climate Change, (b) Freshwater Ecotoxicity and (c) Mineral and Metals.

Compared to the analysis of LLPs, Figure 8 shows the distribution of scrap part replacements across the engine modules. Notably, in contrast to LLP replacements, which had significant contributions from modules like the HPC, HPT and LPT, scrap part replacements show distinct contributions from other modules, such as the HPC module in the category of Climate Change. In contrast, in the other two impact categories the combuster and the HPT have the highest share. It is important to note that within the combuster module no LLPs exist. The combuster scrap parts consists primarily of liner segments, which are exposed to the highest thermal stresses within the engine and therefore need to be replaced more regularly.

Engine Testing Figure 9 provides a comprehensive overview of the environmental impacts of engine testing compared to the other activity types. Besides LLP and scrap part replacement, engine testing significantly contributes to the environmental impact, particularly in the Climate Change and Freshwater Ecotoxicity categories. Accounting for over 10,400 kg CO_2 eq., engine testing alone constitutes more than one-third of the climate change impact, primarily due to the substantial quantities of kerosene consumed during testing. For Freshwater Ecotoxicity, engine testing contributes for nearly a quarter of the environmental impact, while in the category of Minerals and Metals the engine test has no impact.

Maintenance Tasks Throughout all stages of engine maintenance, energy consumption is unavoidable, whether for alloy melting or for operating the maintenance facility and equipment. Figure 10 provides a visual comparison of the various maintenance tasks, namely LLP and scrap part replacement, engine disassembly and assembly, as well as engine testing, across each impact category. When examining the energy consumed during the maintenance processes, it becomes evident that the replacement of parts has no direct impact. However, the energy consumption is a significant factor during the tasks themselves, which require energy for heating as well as electrical energy for lighting and tool usage. Figure 10 illustrates that disassembly and assembly require comparatively higher energy, with assembly exhibiting the highest energy demand in all impact categories. The impact on Freshwater Ecotoxicity, which is not related to energy, arises from the on-site transportation of parts and modules.



(a) Climate Change (b) Freshwater Ecotoxicity (c) Mineral and Metals

Figure 9 – Share of impact category Climate Change over all tasks during engine testing.

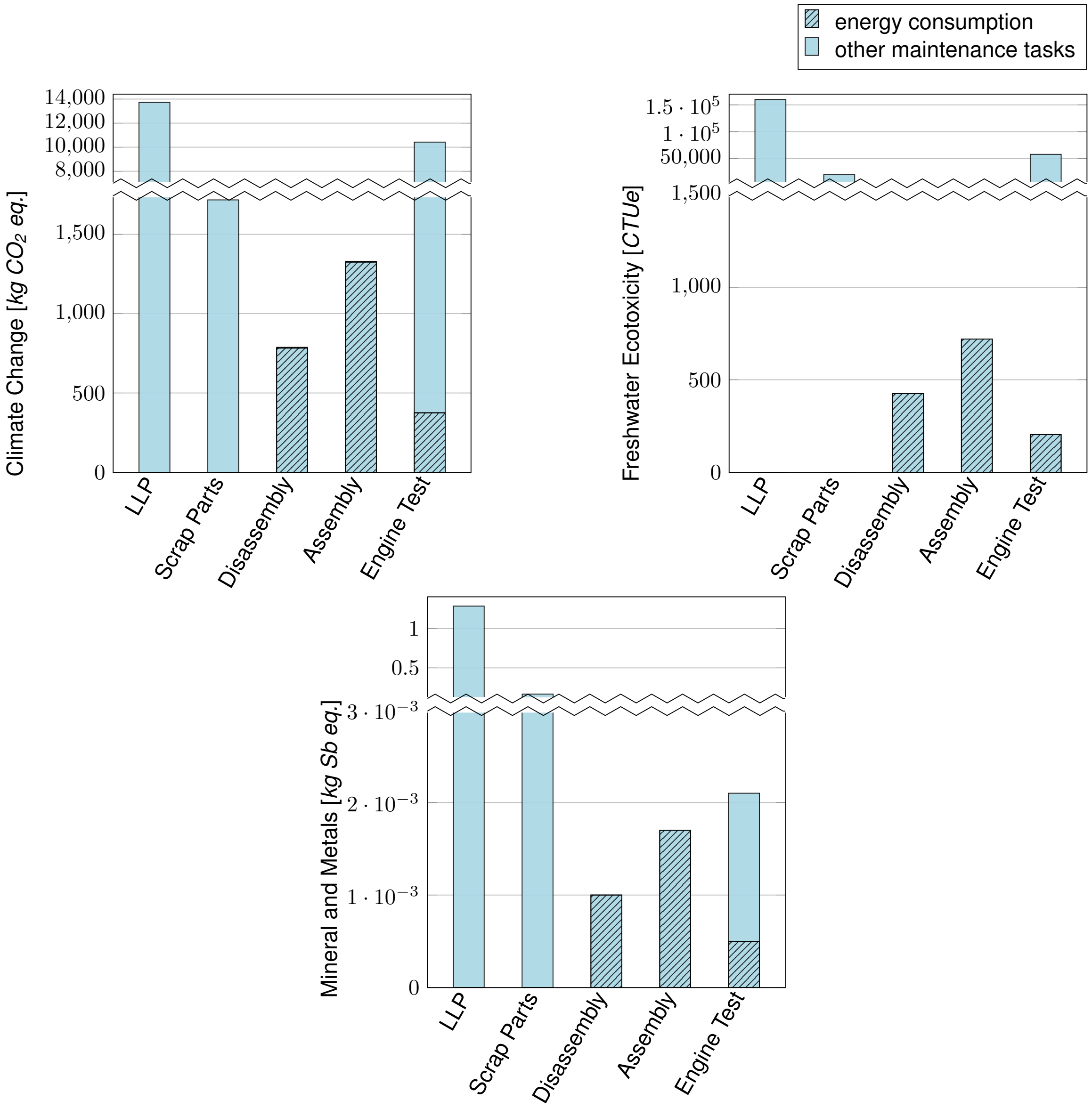


Figure 10 – LCA results with focus on the energy consumption with regard to the impact categories of Climate Change, Freshwater Ecotoxicity and Mineral and Metals.

In comparison to the full ecological impact, the impact of energy usage is relatively minor for engine testing in the categories of Climate Change and Freshwater Ecotoxicity. However, when considered in the context of the overall environmental impact of energy usage throughout the process of LLP replacement, it accounts for approximately 15% of the total energy-related impact.

5.2 Sensitivity-Analysis

A sensitivity analysis is an effective approach to quality improvement, aimed at identifying the significance of inaccuracies. Local analysis, as described in [38], is employed to identify any significant uncertainties. In this study, the following parameters were identified as uncertain: man-hours (electricity), kerosene consumption and scrap weight. Each of these parameters is influenced by individual variables. Man-hours may fluctuate depending on the personnel deployed, while kerosene consumption can vary with the engine and may increase if unexpected issues necessitate repeated tests. Furthermore, the scrap rate is influenced by the engine's previous operational area and thrust rating. LLPs are precisely defined and, therefore not included within this sensitivity study. The uncertainties were determined to lie within a range of plus or minus 20 percent, based on engineering judgment. In Figure 11, the sensitivity analysis is illustrated for the three impact categories Climate Change, Freshwater Ecotoxicity and Mineral and Metals. Thereby represents each point the resulting ecological impact for a specific percentage change in the respective input parameter.

The consumption of kerosene during engine tests exhibited the greatest deviation in terms of Climate Change. A reduction in kerosene consumption of 20% has the potential to result in an overall decrease of 7% or approximately 2,000 kgCO$_2$ eq. In contrast, the influence of electricity and scrap materials is relatively insignificant. Similarly, in the category of Freshwater Ecotoxicity, the effect of kerosene is also the most significant. However, the impact of electricity on the ecological footprint is negligible. The situation is distinct in the category of Mineral and Metals, where kerosene and electricity exert no influence, but logically the mass of replaced scrap parts does.

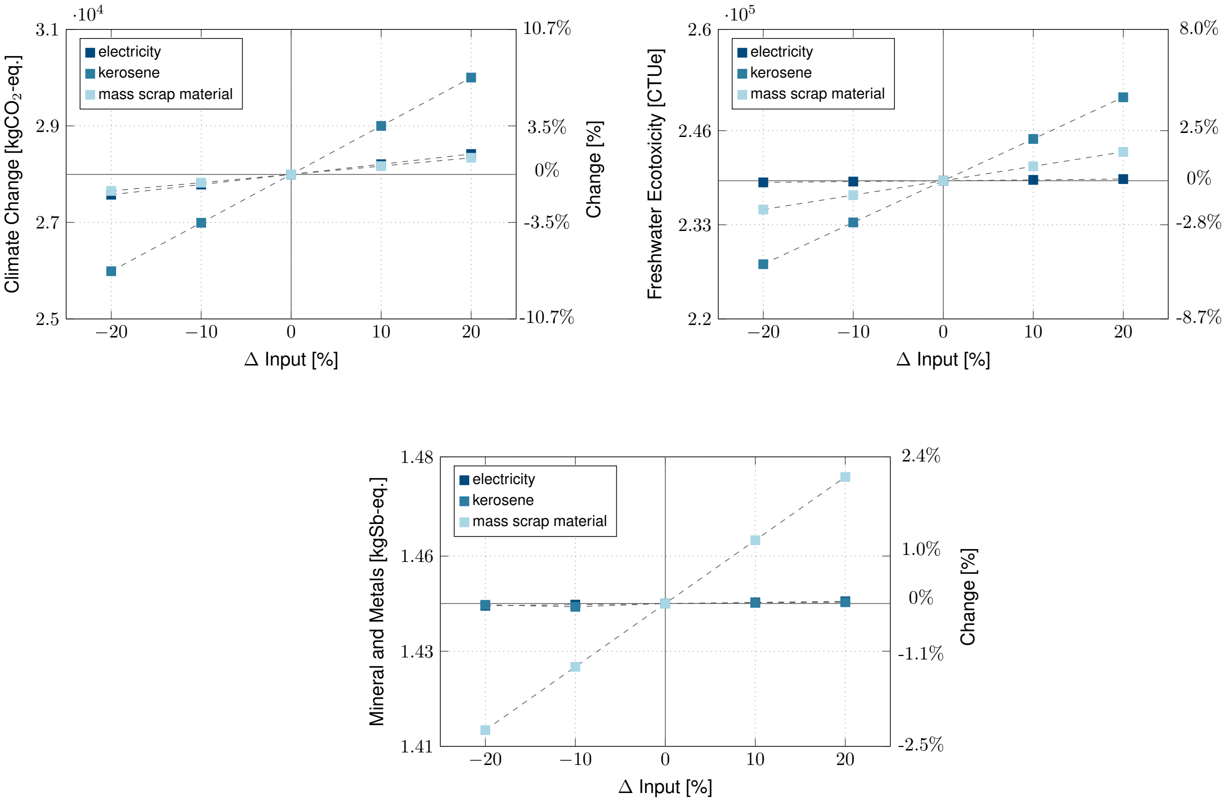


Figure 11 – Results of local sensitivity analysis.

6. Interpretation

The results of this study provide insights into the environmental impact of engine maintenance, offering an overview on the effects of different material usage and the influence of engine testing.

As anticipated, kerosene emerges as a major factor in the ecological assessment of engine maintenance. A sensitivity analysis confirmed the key role of kerosene in comparison to energy consumption and the use of new materials. Nevertheless, the replacement of LLPs should not be underestimated. The total ecological impact in the category of Climate Change is 27,990 $kgCO_2$ eq. per LLP replacement workscope. Maintenance data for an A320 aircraft by Rahn et al. [13] assigns 0.99 $kgCO_2$ eq. per FH to engine shop maintenance, assuming the same number of flight hours between LLP replacements as in this study and including the engine shop and its operation as well as the replacement of LLPs. This aligns with the findings of this study, where 0.89 $kgCO_2$ eq. per FH (1.43 $kgCO_2$ eq./FC) were calculated. It is important to note that this study does not include the repair of parts, which would theoretically result in higher ecological impacts. The lower ecological impact calculated in this study, compared to Rahn et al. [13], can be attributed to several factors. Differences in assumptions regarding material composition, material amount and kerosene consumption, as well as working hours, play a significant role.

Assuming an engine operates for 25 years, this equates to an LLP replacement approximately every 9 years [21], or 2-3 workscopes like the one described in this study. This means that an engine generates at least 83,970 $kgCO_2$ eq. in its lifetime through the replacement of LLPs alone. Compared to the data from literature [13], for one engine this is approx. 5.4% of the GWP of the maintenance of a complete aircraft through its entire life. Nevertheless, the regular investment of 27,990 kg CO2 eq. in engine maintenance leads to a significant improvement in engine performance and safety during operation.

The replacement of LLPs and scrap parts with new ones accounts for approx. 55% of the environmental impact in the Climate Change category. The ecological impact of both LLPs and scrap parts could be further minimized by utilizing previously used components, provided that their continued use in engines is permissible. The influence of used parts on engine maintenance warrants further investigation, particularly for components at the end of their service life.

Furthermore, it was observed that energy consumption during the maintenance process, particularly in engine maintenance, where highly-alloyed materials are frequently replaced and extensive engine testing requires kerosene combustion, constitutes only a minor aspect of the overall ecological impact. This finding contrasts with the conclusions of Meissner et al. [39], who investigated aircraft maintenance and suggested that emissions linked to electrical energy usage in maintenance facilities are the primary ecological contributors.

In this study, planned working hours were employed in lieu of actual working hours, which may impact the precision of the outcomes. Furthermore, the study did not incorporate the concurrent work of multiple individuals on the project. Additionally, the kerosene consumption is based on a standardized test without accounting for troubleshooting activities, resulting in potential discrepancies in the consumption values. These factors contribute to a degree of uncertainty in the results and should be considered during interpretation.

7. Summary and Outlook

Engine maintenance is a critical aspect of the operation and safety of aircraft, and its ecological impact is multifaceted. This study focuses on the ecological impact of a Life Limited Part (LLP) replacement workscope for V2500 engines by conducting a comprehensive Life Cycle Assessment (LCA). By analyzing maintenance activities according to their impact on tasks, materials, and testing, valuable insights are provided into the environmental consequences of engine maintenance in aviation.

The research findings indicate that the replacement of LLPs and the engine test represent the primary contributors to the ecological impact of the activities investigated, which include LLP and scrap part replacement, engine disassembly and assembly as well as testing. Collectively, these activities constitute a substantial portion of the total Global Warming Potential (GWP). Specifically, LLP replacement accounts for the majority of the GWP at 49%, while engine testing contributes to 37%. Even activities, such as the replacement of scrap parts (6% of GWP) and the execution of assembly/disassembly processes (8% of GWP) contribute to the overall ecological footprint. This breakdown enables the identification of maintenance tasks with the greatest ecological impact, thereby providing stakeholders with a detailed understanding of the environmental consequences of their decisions.

The incorporation of industry data in this study significantly enhances the robustness and precision of its findings, thereby underscoring the necessity of such data for conducting comprehensive analyses. To gain a comprehensive understanding of the ecological impact of engine maintenance, it is essential to delve deeper into these factors. Future research will aim to refine and expand the study to include more intensive maintenance workscopes, such as full overhauls. In addition, assessing the ecological impact of engine part repairs and integrating reused parts into maintenance analysis are critical areas for further investigation. Furthermore, the exploration of the potential of recycled materials in component production is expected to hold significant promise for the reduction of ecological impact in alignment with the principles of circular economy. Subsequent research updates are expected to provide insights into these areas.

Understanding the environmental impact of individual tasks, such as the LLP replacement described here, enables a robust analysis of potential savings achievable through the whole engine life by investing in maintenance to ensure a more sustainable operation. Addressing these issues will not only deepen our understanding of the current environmental impacts but also guide future research and industry practices toward a more sustainable aviation sector.

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9. Copyright Statement

Abbreviations

CSLSV	Cycle Since Last Shop Visit
CSN	Cycle Since New
EF	Environmental Footprint
EGT	Exhaust Gas Temperature
FC	Flight Cycle
FH	Flight Hour
GWP	Global Warming Potential
HPC	High Pressure Compressor
HPT	High Pressure Turbine
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LLP Life Limited Part

LPC Low Pressure Compressor

LPT Low Pressure Turbine

MRO Maintenance, Repair and Overhaul

SAF Sustainable Aviation Fuel

TSN Time Since New

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