Time to Replace? A Guide for Sustainable Engine Maintenance Strategies

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ABSTRACT

Aircraft engine maintenance planning is traditionally focusing on questions of economic optimization. This includes repair-versus-replacement decisions and the cost-effective scheduling of maintenance events and relies on operational data, shop visit forecasts, and contractual obligations. Although this approach has been subject of extensive study, the integration of environmental considerations into maintenance planning remains largely overlooked. For example, replacing Life Limited Parts (LLPs) in shorter intervals can improve engine efficiency and reduce fuel consumption, but increases material demand and lead to a higher number of shop visits, causing additional environmental impacts. Postponing replacement conserves resources but may lead to higher operational inefficiencies and greater fuel consumption. Therefore, the objective of this study is to examine the environmental consequences associated with the timing and frequency of LLP replacements. Furthermore, it analyses the impact of different replacement intervals on climate change, material resource consumption and engine performance. A comparative Life Cycle Assessment (LCA) study is conducted to quantify the environmental impacts of replacing LLPs at shorter intervals versus an optimized replacement interval. By varying the LLP usage, this study demonstrates how longer utilization influences the overall environmental impacts. These repercussions are compared to increased fuel consumption due to engine degradation by using a simplified engine performance degradation approach. The findings of the study indicate the significance of varying impacts of different replacement intervals on the overall environmental performance. Furthermore, the study underscores the importance of recycling strategies for improving resource efficiency and sustainability in engine maintenance.

1. INTRODUCTION

The maintenance planning of aircraft engines is a complex process influenced by multiple operational and contractual factors. An engine enters maintenance based on a combination of parameters, including Flight Cycle (FC) and Flight Hours (FH), upcoming scheduled shop visits, associated costs, and contractual obligations with Maintenance Repair and Overhaul (MRO) providers or leasing companies (Ghobbar et al., 2013). While extensive research exists on cost optimization in maintenance planning, including optimization of shop visit intervals, LLP replacements, and scheduling of engine overhauls, environmental considerations remain largely unexplored. Existing studies primarily focus on determining the life cycle costs of engine operation (Seemann et al., 2011), optimizating maintenance reserve payments within engine leasing contracts (Bugaj et al., 2019), analytically modeling the cost impact of of premature LLP replacements (Stojiljković et al., 2021), or improving shop visit scheduling and exchange optimization of LLPs between engines (Cerdeira et al., 2017; Yu et al., 2022). A literature search in Scopus, for example, reveals 155 results related to conventional engine maintenance planning[1], but none addressing sustainable or environmental-driven planning. Previous reviews such as Vrignat et al. (2022) provide comprehensive overviews on the role of sustainable manufacturing and maintenance policies across various industrial sectors, highlighting the relevance of prognostics and health management approaches in optimizing maintenance from a sustainability perspective. In addition, Bouabid et

[1]search term: (”aircraft engine” OR ”turbofan engine” OR ”turboprop engine” OR ”gas turbine” OR ”turbine engine” OR ”life limited parts” OR llp OR ”life-limited parts”) AND (”maintenance schedule” OR ”maintenance plan” OR ”maintenance fleet” OR ”fleet planning”)

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al. (2024) underlies the role of maintenance in achieving sustainability goals in high-risk industries, while Karki and Porras (2021) explores the potential of digitalization to support more sustainable maintenance practices. Moreover, the recent umbrella review by Vasić et al. (2024) identifies key criteria for adopting sustainable maintenance practices across industrial sectors and notes a shift from purely economic towards more balanced environmental and social considerations. However, these studies do not specifically address the aviation sector. Therefore, this gap highlights a critical shortcoming in current maintenance strategies in aviation, as sustainability concerns gain increasing relevance and policies like the European *Fly the Green Deal* highlight the need for more sustainable practices in aircraft maintenance and operations (European Commission, 2022b).

1.1. Life Limited Parts and Critical Raw Materials

One particular aspect of engine maintenance with significant environmental implications is the management of Life Limited Parts (LLPs). LLPs are a characteristic element in aviation maintenance, with few equivalents in other industries. These components have predefined maximum operational limits, known as *hard lives*, beyond which they must be replaced, regardless of their actual condition. Unlike components with *soft lives*, where predictive maintenance strategies have been extensively studied, LLP replacements have seen little optimization. These certified life limits of LLPs, which strongly influence maintenance scheduling, are typically specified by the engine manufacturer based on fatigue tests and regulatory certification requirements (Fornlöf et al., 2016; U.S. Department of Transportation - Federal Aviation Administration, 2017). According to Aircraft Commerce (2008), many LLPs are retired well before reaching their full operational limit. For example, the IAE V2500 engine, commonly used in the Airbus A320, has LLP life limits of 20,000 Engine Flight Cycles (EFCs) across all modules. However, LLPs in these engines are often replaced after only 14,000 to 17,000 EFCs (Aircraft Commerce, 2008), leaving a substantial remaining life between 3,000 and 6,000 EFCs unutilized. This is primarily due to the economic rationale of avoiding subsequent shop visits and not due to safety concerns, as these parts are designed with sufficient safety margins and are typically removed far before reaching their maximum allowable life. However, it is often more cost-effective to address all required maintenance tasks in one shop visit than to schedule multiple visits with associated downtime and operational costs. These remaining so-called stub-lives can be equivalent to up to a quarter of the component's full lifespan, depending on the maintenance management of the operator (Aircraft Commerce, 2008). In general, the consolidation of multiple maintenance tasks during a shop visit can be viewed as a form of opportunistic maintenance aiming to reduce downtime and logistic costs. The concept of opportunistic maintenance for aircraft engines was already described by Dinesh Kumar et al. (1999), while Cavalcante et al. (2024) explained this concept especially for part replacements.

These premature replacements contribute, besides of an increase in the costs per flight cycle (Stojiljković et al., 2021), significantly to the environmental impact, including material usage. Currently, decommissioned LLPs are either scrapped or stored, although the literature reports only limited cases of reuse or resale. As a result, a substantial share of the materials used in manufacturing these high-performance components, including rare and critical metals like titanium, nickel, rhenium or vanadium (Hoff et al., 2024; Voigt et al., 2023), is wasted or downcycled, meaning that recovered metals are repurposed for lower-grade applications instead of being reused in aviation (Airbus, 2022). Many of these materials are not only expensive and environmentally impactful in their production, but are also listed as Critical Raw Materials (CRMs) by the EU and the U.S. due to their economic importance and potential supply risks (European Commission, 2023; Burton, 2022). The reliance on CRMs introduces additional vulnerabilities to supply chain disruptions, as evidenced by past and present shortages, such as the titanium supply crisis affecting MRO supply chains (Aerotime, 2023; Dubois, 2025). Additionally, regulations such as the EU's *Critical Raw Materials Act* (European Commission, 2022a) and the *Clean Industrial Deal* (European Commission, 2025) emphasize the need for more sustainable material usage in aviation maintenance.

1.2. Replacement Intervals

Maintenance strategies are defined by Sun et al. (2023) as a set of rules combining preventive and proactive maintenance tasks. The LLP replacement is one of the main problems in engine maintenance strategies (Figueroa Mayordomo et al., 2010). Depending on contractual aspects such as the end of the leasing contract and the return conditions, the airlines must identify the best time to replace the LLPs. Traditionally, the maintenance strategies of engine operators differ in the balance between shop visit costs and shop visit rate and are measured in cost per hour (Figueroa Mayordomo et al., 2010). While the shop visit rate is affected by the Time-On-Wing policy and the LLP replacement schedule, the shop visit costs depend on the engine performance and the component condition, resulting in different workscope levels during maintenance (Figueroa Mayordomo et al., 2010). But Ackert (2011) showed that running LLPs until their life limit may not be the cost-optimized strategy.

If the described aspects are supplemented by the aspect of environmental sustainability, the multi-criteria problem is extended by an additional factor. Extending component usage could reduce dependency on CRMs, decrease material waste, and ultimately enhance supply chain resilience (Hoff et al., 2025). Therefore, maximizing LLP lifetimes and optimizing replacement timing to reduce material demand could serve as a promising approach. The premature replacement also leads to an increased number of shop visits. Unfortunately, the trade-offs between performance degradation, material conservation, and environmental impact have not been thoroughly explored in existing literature.

In Figure 1, the decision-making process for LLP replacements is illustrated. After the shop visit is triggered, the decision must be made whether the LLPs needs to be replaced or not. If the LLPs are replaced, but their remaining life is insufficient for reuse, they are typically scrapped instead of being reintroduced into the market (critical decision path). This occurs because engines with LLPs having only a small number of remaining cycles are not economically viable to get reassembled. Consequently, as already described, premature LLP replacements can lead to excessive material waste, increasing the environmental footprint of maintenance activities.

On the other hand more regular maintenance events reduce the fuel consumption of an engine, as with each shop visit an engine gets cleaned and repaired to regain efficiency. These so-called *Performance Restoration (PR)* workscopes restore the efficiency primarily by inspecting, cleaning, and repairing airfoils, which are exposed to fouling, erosion, or deposition during operation. These degradation directly affect the engine's Specific Fuel Consumption (SFC), and their removal during a maintenance event leads to measurable fuel burn improvements. PR workscopes are typically scheduled between two LLP replacements and allow to regain a large portion of lost performance. (Ackert, 2011)

The resulting environmental optimization thus requires evaluating both effects - operational efficiency as well as material demand - simultaneously, as frequent restorations increase material use but reduce operational fuel consumption. A sustainable maintenance strategy should therefore also incorporate additional indicators, such as the trade-off between fuel efficiency and maintenance timing, circular economy principles in MRO practices, or regulatory incentives. This paper does not propose a definitive solution but rather highlights the parameters that need to be integrated into existing maintenance strategies to enable more sustainable decision-making.

Therefore, the goal of this paper is to quantify the environmental impact of premature LLP replacements and explore potential improvements in replacement intervals. A key consideration is LLP production and disposal, which contribute significantly to the environmental footprint and include significant amounts of CRMs. This study aims to take the first step to bridge the gap between economic and environmental considerations in engine maintenance planning.

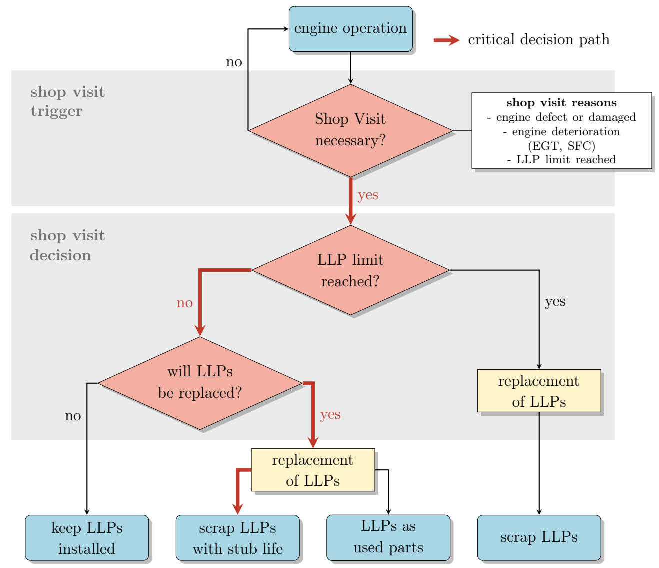


Figure 1. Maintenance decision process of LLP replacement.

2. ENVIRONMENTAL ANALYSIS

For this study, the IAE V2500 engine was selected as a case study. According to Aircraft Commerce (2008), the LLPs in the V2500 engine are designed for a maximum of 20,000 cycles, but in practice, these parts are typically replaced after 14,000 to 17,000 cycles, resulting in the premature discarding of usable components.

The LCA methodology, based on DIN EN ISO 14040 (European Committee for Standardization, 2006) and DIN EN 14044 (European Committee for Standardization, 2018), is employed to quantify the environmental impact of premature replacements. The LCA process consists of four distinct steps: First, during the *goal and scope* phase, the focus of the study on the environmental impact of LLPs replacement as well as the system boundaries are defined. Within this analysis both the repair and the replacement of parts that are not LLPs are excluded as well as the transportation of all parts or engines to or from the maintenance site. However, the material replacement of LLPs, their manufacturing, engine testing after each shop visit, and the environmental impacts from hangar operations (e.g., lighting, heating, and tool operation) are taken into account for two types of shop visit - PR (cleaning and minor repairs) and LLP replacement. These boundaries provide the framework for the subsequent step, which involves the *collection* of all relevant *inputs* (e.g., material resources for part replacement and energy consumption for hangar operation) and *outputs* (e.g., expected waste during maintenance and emissions during flight operation and engine testing). In the third step, these inputs and outputs are evaluated across various *environmental impact categories* as part of the Life Cycle Impact Assessment (LCIA). Finally, the fourth step focuses on the *interpretation and discussion* of the results, considering the initially established goal and scope. (European Committee for Standardization, 2006, 2018)

The total environmental impact in this study is assessed based on the functional unit of '*x* LLP replacements per 60,000 cycles of operation', where *x* is varying depending on the maintenance interval. A comparative analysis is employed in order to provide an overview of the results. The LCA calculations are based on the open-source, python-based brightway2 framework (Mutel, 2017) and the ecoinvent 3.9.1 database (Wernet et al., 2016), while the Environmental Footprint (EF) 3.1 method (Andreasi Bassi et al., 2023) is employed for the LCIA.

In the present analysis, the primary focus was on two impact categories, namely Climate Change (CC) and Resource Use - Minerals & Metals (MM). While the MM impact category does not represent the CRM thematic directly it is nonetheless applied to demonstrate the discussed raw material dimension. Table 1 illustrates the used environmental data and their corresponding references. The values are expressed as midpoint indicators following the LCIA methodology: CC, given as Global Warming Potential (GWP) in kg CO_2 equivalents, and resource depletion of MM, expressed in kg antimony equivalents (Sb eq.). These values represent the aggregated environmental burden from upstream processes such as raw material extraction, energy consumption, manufacturing, and processing required to produce or operate the respective system elements (e.g. LLPs, shop operation, test run). The values employed in this study as well as the results of all impact categories are provided in full in the appendix of this study.

To assess the environmental impact of different replacement intervals, the two environmental impact categories CC and MM are considered and their cumulative environmental impact is calculated as following:

$$\mathrm{CC}_{\mathrm{total}} = \underbrace{\sum_{j=1}^{n_{\mathrm{cycle}}} m_{\mathrm{fuel,j}} \cdot \mathrm{CC}_{\mathrm{fuel,j}}}_{\text{Flight impacts}} + \underbrace{\sum_{i=1}^{x} \mathrm{CC}_{\mathrm{PR,i}} + \sum_{i=1}^{y} \mathrm{CC}_{\mathrm{LLP,i}}}_{\text{Maintenance impacts}} \tag{1}$$

$$\mathrm{MM}_{\mathrm{total}} = \underbrace{\sum_{j=1}^{n_{\mathrm{cycle}}} m_{\mathrm{fuel,j}} \cdot \mathrm{MM}_{\mathrm{fuel,j}}}_{\text{Flight impacts}} + \underbrace{\sum_{i=1}^{x} \mathrm{MM}_{\mathrm{PR,i}} + \sum_{i=1}^{y} \mathrm{MM}_{\mathrm{LLP,i}}}_{\text{Maintenance impacts}} \tag{2}$$

with

$\mathrm{CC}_{\mathrm{total}}$	total environmental impact in CC
$\mathrm{CC}_{\mathrm{fuel,j}}$	environmental impact in CC of fuel production & combustion
$\mathrm{m}_{\mathrm{fuel,j}}$	mass of consumed fuel
$\mathrm{CC}_{\mathrm{PR}}$	environmental impact in CC of PR workscope
$\mathrm{CC}_{\mathrm{LLP}}$	environmental impact in CC of LLP replacement
$\mathrm{MM}_{\mathrm{total}}$	total environmental impact in MM
$\mathrm{MM}_{\mathrm{fuel,j}}$	environmental impact in MM of fuel production
$\mathrm{MM}_{\mathrm{PR}}$	environmental impact in MM of PR workscope
$\mathrm{MM}_{\mathrm{LLP}}$	environmental impact in MM of LLP replacement
x	number of PR shop visits
y	number of LLP shop visits

For $\mathrm{CC}_{\mathrm{total}}$, total greenhouse gas emissions related to fuel use over the aircraft's lifetime, including both combustion emissions and upstream emissions from fuel production and supply, are calculated based on data from the International Aerospace Environmental Group (IAEG) (2024) (see Eq. 1). This constitutes a simplified approach, as it neglects the specific timing and geographic location of emissions, which would be required for a more detailed analysis. For MM, no equivalent value is available, as multiple factors influence kerosene combustion during operation. However, it can be assumed that the impact of MM during operation is relatively low and does not significantly affect the study's results. Therefore, for $\mathrm{MM}_{\mathrm{total}}$, only the production of kerosene is considered, in addition to the impacts due to the shop visit.

3. MODELING OF MAINTENANCE INTERVALS

The degradation of the engine over time is an important factor in determining the optimal maintenance interval. In this study, a rule-based, deterministic model is used to evaluate different LLP replacement intervals over the engine lifetime. The model follows a scenario-based what-if approach to quantify the ecological implications of varying maintenance decisions. The engine deterioration is modeled primarily through two key parameters: fuel consumption and Exhaust Gas Temperature (EGT) margin. While the EGT margin serves as an indicator of thermal efficiency degradation, fuel consumption is considered in the analysis due to its significant contribution to both environmental impact and operating costs. Since fuel consumption directly correlates with the CO_2 emissions, it is included as a key factor alongside the material impact of LLP replacements.

Engine performance degrades over time due to material wear, fouling, and thermomechanical stress. The degradation status is measured by the EGT margin, which describes

Table 1. Relevant values of the LCA calculations in the impact categories CC and MM.

Parameter	Impact Category CC		Impact Category MM	
	Value [kg CO_2 eq.]	**Reference**	**Value** [kg Sb eq.]	**Reference**
LLP materials	13,093	(Oestreicher et al., 2024)	1.0986	(Oestreicher et al., 2024)
LLP manufacturing	1,475	(Oestreicher et al., 2025)	0.0012	(Oestreicher et al., 2025)
LLP replacement shop operation	3,822	(Oestreicher et al., 2024), (Rahn et al., 2024)	0.0089	(Oestreicher et al., 2024), (Rahn et al., 2024)
performance restoration shop operation	3,094	(Oestreicher et al., 2024), (Rahn et al., 2024)	0.0080	(Oestreicher et al., 2024), (Rahn et al., 2024)
engine test run	10,399	(Oestreicher et al., 2024)	0.0019	(Oestreicher et al., 2024)
kerosene production & combustion [per kg]	3.846	(IAEG, 2024)	6.13×10^{-7}*	(Oestreicher et al., 2025)

** only for kerosene production*

the margin between the maximum operational EGT, defined by the engine's manufacturer, and the currently measured EGT. The EGT margin decreases progressively as the engine accumulates cycles, with a more distinct degradation rate during the early stages of operation. The degradation function for the EGT margin is, based on Justin and Mavris (2015), given in Eq. 3. The fuel consumption increases accordingly (see Eq. 5) based on the actual SFC value (see Eq. 4), where k represents the SFC increase per 1°C EGT degradation as listed in Table 2 and $\text{EGT}_{\text{start}}$ characterizes the EGT margin after the last shop visit.

$$\text{EGT}_{\text{current}} = \text{EGT}_{\text{start}} - 0.104 \cdot \left(\text{EFC}^{0.659}\right) \tag{3}$$

$$\text{SFC}_{\text{current}} = \text{SFC}_{\text{base}} \cdot (1 + k \cdot (\text{EGT}_{\text{base}} - \text{EGT}_{\text{current}}) \tag{4}$$

$$\text{m}_{\text{fuel}} = \text{SFC}_{\text{current}} \cdot T_{\text{cruise}} \cdot t \tag{5}$$

Maintenance events are integrated into the model to simulate PRs and LLP replacements. These maintenance actions partially or fully recover the engine's performance by resetting the EGT margin to predefined levels. The model differentiates between:

- **LLP Replacements:** Conducted at fixed cycle intervals (e.g., 12,000 – 20,000 cycles), restoring the EGT margin to 80°C (after first LLP replacement), 75°C (2nd LLP replacement), 70°C (3rd LLP replacement), or 65°C (4th LLP replacement), depending on the number of previous replacements. These values are used to derive the corresponding value $\text{EGT}_{\text{start}}$.
- **Performance Restoration:** Conducted at mid-intervals between LLP replacements, restoring $\text{EGT}_{\text{start}}$ by -3°C compared to the last LLP reset (e.g. the former LLP replacement restored the EGT margin to 75°C, therefore the following PR shop visit restores the EGT margin to 72°C). This is based on the assumption that a PR workscope can almost, but not completely, restore the EGT margin compared to a full engine overhaul, which is in this study an LLP replacement.

In Table 2 additional assumptions of the model are given. Each engine is simulated for a service life of 60,000 cycles and it is assumed that each flight cycle has a duration of two hours.

Figure 2 illustrates exemplary the impact of different LLP replacement intervals (12,000 vs. 20,000 cycles) on EGT margin degradation (Fig. 2a) and fuel consumption (Fig. 2b) over 25,000 cycles. In the upper graph, the EGT margin continuously decreases as the engine operates, with resets occurring after each maintenance event. Every second shop visit is an LLP replacement, restoring the EGT margin significantly (e.g., at 20,000 cycles for LLP 20k and at 12,000 cycles for LLP 12k). The intermediate shop visits, occurring at half the LLP lifetime, are PR events, which provide only a partial recovery of the EGT margin compared to an LLP replacement shop visit. The interval with more frequent LLP replacements (LLP 12k) maintains a higher lifetime-averaged EGT margin, while the longer interval (LLP 20k) leads to lower margins before each reset.

In turn, Figure 2b demonstrates the relative fuel consumption. In this instance, the replacement interval of 20,000 cycles is employed as the baseline interval, with the other interval demonstrating its deviation from the baseline. Two metrics are used to compare the impact of the different LLP replacement intervals: cyclewise difference and cumulative difference.

The cyclewise difference (dotted lines) represents the relative deviation in fuel consumption at each cycle. It is calculated as given in Eq. 6, where $\text{m}_{\text{fuel, cycle [i]}}$ is the fuel consumption of the evaluated maintenance interval at cycle i and $\text{m}_{\text{fuel, base [i]}}$ represents the fuel consumption of the baseline interval (LLP 20k) at the same cycle. The cumulative difference (solid

Table 2. Model Assumptions and Descriptions

Parameter	Description	Value	References
EFC	EFC since last shop visit (used in degradation formula)	0 to max. 20,000 (reset at SVs)	
EGT_{base}	initial EGT margin at the beginning of engine life	85°C	assumption based on Aircraft Commerce (2008)
EGT_{start}	EGT margin after a shop visit (reset depending on maintenance step)		
$EGT_{current}$	EGT margin at a specific cycle (including degradation)		
k	relative SFC increase per 1°C EGT degradation	0.1%	Justin and Mavris (2015)
m_{fuel}	fuel mass per cycle (derived from thrust, time, and degraded SFC)		
SFC_{base}	SFC at the first engine cycle (cruise conditions)	0.57 lb/h/lbf	Jenkinson, Simpkin, and Rhodes (1999)
$SFC_{current}$	SFC at specific cycle, accounting for EGT degradation		
t	time per engine cycle (FH/FC)	2.0 h	
T_{max}	maximum thrust of the engine V2527	24,800 lbf	Aircraft Commerce (2008)
T_{cruise}	cruise thrust of the engine V2527 (20% of max. thrust)	4,960 lbf	

lines) accounts for the total accumulated fuel deviation over all previous cycles (cf. Eq. 7), providing a long-term comparison of the replacement intervals.

$$\Delta m_{\text{fuel, cyc}}[\%] = \frac{m_{\text{fuel, cycle}[i]} - m_{\text{fuel, base}[i]}}{m_{\text{fuel, base}[i]}} \cdot 100 \quad (6)$$

$$\Delta m_{\text{fuel, cum}}[\%] = \sum_{j=1}^{i} \frac{m_{\text{fuel, cycle}[j]} - m_{\text{fuel, base}[j]}}{m_{\text{fuel, base}[j]}} \cdot 100 \quad (7)$$

It is evident that the fuel consumption is reduced in the LLP 12k interval over the 25,000 cycles when compared to the base interval. The cyclewise representation demonstrates the reason for this, as each shop visit improves the fuel consumption and thus influences the cumulative difference to the base interval. However, the cyclewise perspective also reveals an important detail: at 10,000 cycles the base interval has a PR shop visit, which temporarily improves its fuel efficiency. In this period the LLP 12 k interval appears less favorable, with a relatively higher cyclewise fuel consumption. But it does not offset the cumulative advantage gained before. At 12,000 cycles the LLP 12k interval has its first LLP replacement, which again results in an improved fuel efficiency compared to the base interval. This alternating periods of relative advantages and disadvantages continue throughout the whole engine life. It also explains the oscillating shape of the cumulative curve, which reflects both the immediate and long-term effects of different maintenance intervals.

4. ANALYSIS OF MAINTENANCE INTERVALS

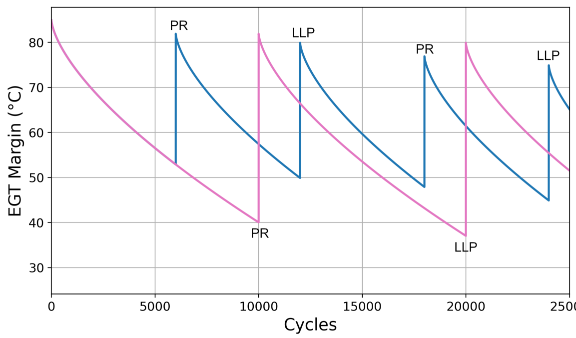
Building upon the deterministic model discussed in the previous section, this section addresses the challenges associated with the premature replacement of components that have a limited remaining life. Even components with up to 25% of their original lifespan remaining generally face a low probability of being effectively reused. Given these challenges, this section explores various replacement intervals and their associated environmental impacts, aiming to provide a understanding of the environmental consequences of different replacement intervals.

4.1. Replacement Intervals

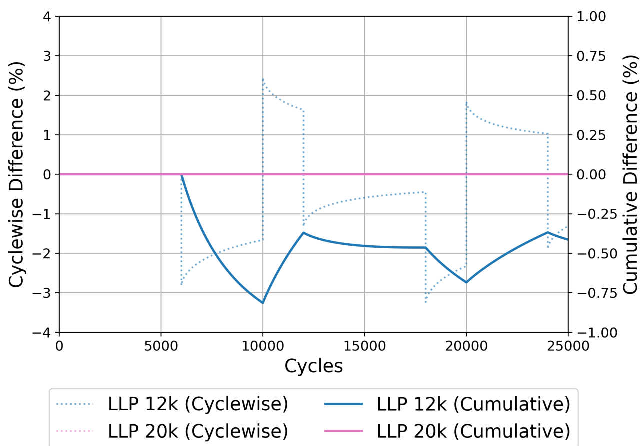
All replacement intervals are modeled for a duration of 60,000 cycles. At half of the time between each LLP replacement event, a PR shop visit is included to restore the EGT margin and simulate a typical real-world practice. The model is iterating over 60,000 cycles while dynamically adjusting fuel consumption and environmental impacts based on the degradation and maintenance schedules.

The following maintenance intervals are considered in this study:

- **LLP 20k (Base Interval):** Replacement of LLPs after 20,000 cycles, as per the original design limit.
- **LLP 12k:** Replacement of LLPs after 12,000 cycles, representing the minimum modeled life.
- **LLP 15k:** Replacement of LLPs after 15,000 cycles, reflecting typical real-world practice.



(a) EGT margin degradation over 25,000 cycles for LLP intervals of 12,000 and 20,000 cycles.



(b) Fuel consumption difference relative to LLP 20k.

Figure 2. EGT margin and fuel consumption comparison for LLP intervals of 12,000 and 20,000 cycles.

- **Extended Intervals:** Extension of the LLP 15k interval with additional LLP usage beyond 15,000 cycles, considering 5% (i.e., +750 cycles, resulting in a replacement at 15,750 cycles - **LLP 15.75k**), 10% (16,500 cycles - **LLP 16.5k**), 20% (18,000 cycles - **LLP 18k**), or 30% (19,500 cycles - **LLP 19.5k**) more cycles to simulate potential lifespan extensions.

It is important to acknowledge, that all intervals exclusively contain scheduled maintenance events. Conversely, unscheduled events, such as part damages or early removals, are not encompassed within this analysis.

4.2. Analysis of Replacement Intervals

The three graphs shown in Figure 3 illustrate the differences in fuel consumption (Fig. 3a) as well as the impact categories CC (Fig. 3b) and MM (Fig. 3c), comparing both cyclewise and cumulative data.

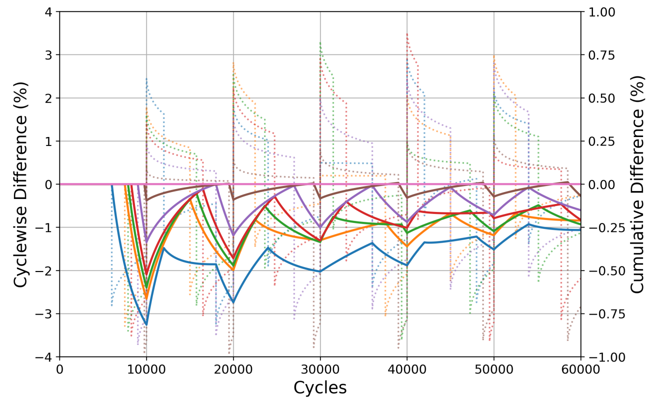
Fuel Consumption The analysis of the fuel consumption graph clearly demonstrates that frequent LLP replacements (e.g., LLP 12k, blue solid line) lead to more significant fuel savings, primarily due to the increased number of shop visits, which improve engine efficiency. However, the most substantial difference between the replacement intervals is observed in the early stages of engine operation. Initially, more frequent LLP replacements result in larger fuel savings due to frequent shop visits and the subsequent efficiency improvements. However, over the entire life cycle of the engine, the improvements in fuel consumption become less pronounced, with the gap between the intervals narrowing as the engine ages. This trend is explained by the initial fuel savings achieved directly after the first shop visits, which diminish over time as the base interval also benefits from performance improvements. When comparing the extreme intervals (LLP 12k vs. LLP 20k), the reduction in fuel consumption by the end of the engine's life is less than 0.3 percentage points, showing that while early improvements are more significant, they are stabilizing as the engine continues to operate.

Climate Change The impact on CC in this analysis is predominantly related to fuel consumption, as changes in fuel burn directly translate into significant variations in greenhouse gas emissions. In contrast, the contribution of part manufacturing to CC is comparatively minor. Intervals with frequent LLP replacements (such as LLP 12k) show a significant reduction in CC impact due to the improved fuel efficiency resulting from more frequent shop visits. Conversely, as the LLP replacement interval increases, the improvements in fuel efficiency and, consequently, the reduction in CC impact diminish. In Table 3 it is shown that the environmental impact of the maintenance itself is with maximal 0,03% negligible compared to the amounts of kerosene consumed to power the engine over the whole life, which result in similar curves in fuel consumption and CC. However, without these environmental investments from maintenance the impact of the consumed fuel would be much higher, besides the fact that the engine would not achieve as many flown cycles without any maintenance performed. By the end of the engine's life, the total reduction in CC impact is less than 0.3 percentage points, underscoring the conclusion that although frequent LLP replacements offer short-term environmental benefits, the long-term CC impact remains relatively stable across different maintenance intervals.

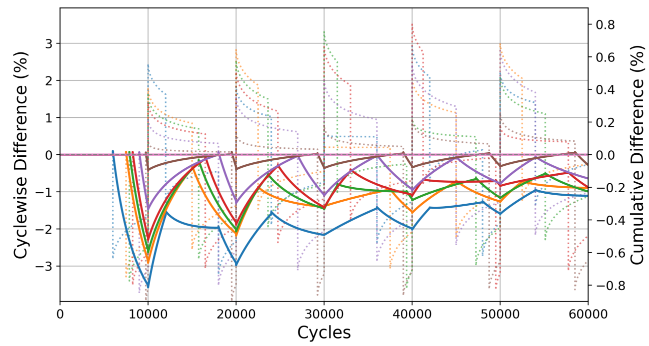
Resource Use - Minerals & Metals Frequent LLP replacements (e.g., LLP 12k) lead to an increase in resource consumption due to the necessity for more frequent part replacements, resulting in a greater environmental impact. The greatest differences in MM usage are observed in the early stages of engine operation, with more frequent replacements leading to a significantly higher demand for raw materials. However, as the engine ages, the differences in resource consumption begin to level off, as it is also the case with the other two categories. Again, this effect can be attributed to the significant improvement in fuel consumption after the first shop visit of each observed interval, which initially creates a cumulative advantage that gradually diminishes as the base interval also undergoes shop visits. It should be noted that the observed trends do not reflect a direct link between fuel consumption and resource use, but rather the combined effect of maintenance timing on both engine efficiency and part replacement frequency. By the end of the engine's life, the consumption of resources (MM) shows a worsening of 2% for the frequent replacement intervals compared to the base interval (LLP 20k), highlighting the long-term environmental cost of increased material usage due to frequent replacements. The impact of maintenance in MM reaches from 2.26% to 4.43%, as shown in Table 3. However, Figure 3c clearly shows that the intervals LLP 16.5k and LLP 19.5k have shop visits shortly before the expected end of engine life, specifically at 57,750 cycles (PR shop visit for LLP 16.5k) and 58,500 cycles (LLP replacement for LLP 19.5k). Adjusting the maintenance schedule or reducing respectively extending their life time could result in an improvement of the overall of the MM impact.

It is evident that the fuel consumption of all replacement intervals exhibits an enhancement in comparison to the base interval, a phenomenon that is also observed in the impact category CC. Conversely, the impacts of MM demonstrate a decline in efficiency when compared to the base interval. Table 3 demonstrates the overall outcomes over the entire engine's life in relation to the base interval as well as the percentage of the maintenance. The results in each impact category as well as the overall consumed fuel are available in the appendix of this study. Nevertheless, it can be seen that the replacement interval LLP 15.75k represents the most efficient interval besides the base interval, as it avoids a notable amount of inefficient, i.e. fuel-consuming, cycles due to the optimal timing of maintenance tasks over the engine's life. As demonstrated in Table 3, this interval achieves the second highest fuel efficiency, surpassed only by the interval LLP 12k, which is also the case for impacts of CC. Notably, the LLP 15.75k interval also shows the optimal result in terms of MM impact when compared to all other intervals and the base interval. While the base interval is regarded as the most advantageous from perspective of MM, the LLP 15.75k interval emerges as the optimal choice in terms of operational efficiency.

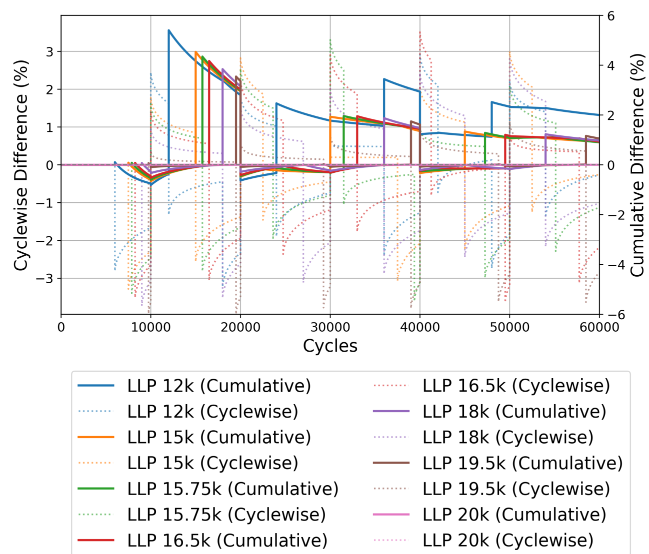
It should be noted that the relative improvements do not follow a strictly linear trend. This is primarily caused by the non-linear engine deterioration and the specific timing of maintenance events. Depending on the interval certain inefficient cycles may or may not be included in the engine's life. As a result intervals like LLP 15.75k avoid a disproportionate share of low-efficient cycles, while others (e.g. LLP 16.5k or LLP 18k) retain such phases longer. This effect can lead to small, counter-intuitive differences in relative impact values.



(a) Difference in fuel consumption.



(b) Difference in the impact category CC



(c) Difference in the impact category MM

Figure 3. Environmental impact differences by LLP replacement intervals (cyclewise + cumulative).

Table 3. Absolute and relative lifetime results.

Replacement Interval	Number of LLP Replacements	Wasted Life per LLP Set	Average EGT margin	Relative Change			Impact MRO	
				Fuel	CC	MM	CC	MM
LLP 12k	4	40.0%	54.1°C	−0.27%	−0.25%	+2.00%	0.030%	4.43%
LLP 15k	3	25.0%	53.6°C	−0.21%	−0.20%	+0.92%	0.023%	3.35%
LLP 15.75k	3	21.3%	53.8°C	−0.23%	−0.23%	+0.90%	0.023%	3.36%
LLP 16.5k	3	17.5%	53.5°C	−0.21%	−0.20%	+0.93%	0.023%	3.35%
LLP 18k	3	10.0%	52.9°C	−0.15%	−0.15%	+0.97%	0.023%	3.35%
LLP 19.5k	3	2.5%	52.1°C	−0.07%	−0.06%	+1.05%	0.023%	3.35%
LLP 20k	2	0.0%	51.4°C	0.00%	0.00%	0.00%	0.015%	2.26%

A closer look at the values in Table 3 reveals that a considerable share of the MM impact increase for shorter intervals is driven by maintenance activity itself. For instance, LLP 12k shows a total MM increase of 2.00%, while the increase in maintenance-related MM emissions amounts to 2.17 percentage points. This suggests that improved engine performance from frequent shop visits offsets part of the added maintenance burden, in this case by 0.17%. For LLP 15.75k, this compensation effect is even higher, reaching 0.20%. A similar observation can be made in the impact category CC, where the overall impact is dominated by fuel consumption. The direct maintenance-related contribution is minimal, e.g. for LLP 12k it amounts to only 0.03% (compared to 0.015% in the base interval). Consequently, the net benefit in CC is primarily driven by improved fuel efficiency, amounting to a total of –0.25% for LLP 12k. This comparison further underscores that in contrast to MM, where maintenance plays a major role, the reduction in CC impact is almost entirely due to operational performance gains.

However, it is important to note that a change of the modeled life limit of the engine can change these impressions, as the omission of the last LLP replacement of the interval LLP 19.5k results in a reduction of the MM impacts with an potentially small fuel consumption increase. It is therefore essential to consider all relevant aspects to make a well-reasoned decision.

5. DISCUSSION OF ENVIRONMENTAL OPTIMIZATION

The results underscore the importance of balancing maintenance schedules to optimize environmental outcomes. Frequent LLP replacements lead to improved engine efficiency and fuel savings, resulting in a reduction in fuel consumption and impact in the category of CC. However, these benefits are counterbalanced by the increased demand for raw materials. As expected, the impact of MM increases in proportion to the frequency of LLP replacement, highlighting the trade-off between operational efficiency (fuel savings) and resource use.

However, a more nuanced view emerges when considering the full life cycle performance of each replacement interval. Notably, the interval with a slightly extended schedule of 15,750 cycles yielded the lowest overall impact, besides the base interval, across all three analyzed categories — fuel consumption, CC, and MM. As the impacts in the MM category have the lowest additional impact at +0.90%, and the fuel consumption and therefore also the impact in CC has the second highest improvement compared to the base interval with -0.23%. This result illustrates that even minor shifts in maintenance intervals and shop visit timing can influence environmental performance. The optimal alignment of LLP replacement and PR workscopes can reduce inefficient operational phases and thereby enhance overall sustainability.

It can be stated that extending the life of LLPs reduces the impact in the MM category per flight cycle; however, the impact on CC is increased. Achieving balance in sustainable maintenance planning is therefore of crucial importance. However, it should be noted that within the framework of an LCA, the impact categories addressed in this analysis are not the only ones to be considered. The results for the additional categories according to the Environmental Footprint (EF) 3.1 method can be found in the appendix. In principle, it can be said that focusing on just one impact category, such as CC, in maintenance planning is not effective, as this often results in burden shifting, whereby improvements in one category are accompanied by significant deterioration in another. This phenomenon is demonstrated in this study, where improvements in CC are achieved at the expense of increased impacts in MM. This further underscores the the potential benefit of multi-criteria decision making (MCDM) approaches, which could enable balancing multiple environmental impact categories alongside economic or operational considerations for environmental optimized maintenance strategies.

This also leads to the question of how to effectively manage these used LLPs in the maintenance process. The probability of reusing components increases with the Remaining Useful Life (RUL). In practice, it is often challenging to fully utilize the RUL of parts as engines are not only subject to scheduled maintenance, but also to unplanned events. In such cases, replacing parts with newly produced ones can often be more economically efficient than reusing components. For example, it is not worth rebuilding an engine with used parts that have only 3,500 cycles left, as it would be the case if parts from the LLP 16.5K interval were reused. Furthermore, each shop visit necessitates a substantial energy investment itself, and the mandatory engine testing additionally increases its environmental impact. In this context, it may often be more environmentally efficient to replace components rather than extending their use. Nevertheless, it is important to recognize that parts are typically not utilized until the end of their defined life, and therefore valuable materials are frequently lost for the aviation sector. Whereby, future developments in reuse strategies and advanced life prediction methods may also allow for higher utilization of remaining part life, potentially influencing the environmental trade-offs discussed in this study.

A consequential issue lays in the allocation of these environmental costs fairly between operators. An operator who replaces components more frequently will have a greater impact in the category of MM, while one who adopts a strategy of longer fleet lifespans may cause a slightly higher impact in CC due to increased fuel consumption but benefit from lower resource consumption. It is essential to find a balanced approach that accounts for these distinct environmental trade-offs. Such an approach has the potential to contribute to the development of more sustainable practices, as well as improving supply chain resilience and supporting material independence.

6. CONCLUSION

The present paper introduced an exploratory approach to shed light on the challenges and opportunities associated with LLP replacement intervals, as well as the broader issue of material criticality in the aerospace sector. The investigation encompassed the environmental impacts of different LLP replacement intervals, with a particular focus on their influence on the environmental impact categories of MM and CC. The combination of cycle-based fuel consumption analysis and life cycle assessment enabled the identification of trade-offs between operational efficiency and resource conservation. The findings obtained from this study offer several key insights that provide a foundation for future research.

1. **Environmental impact depends on the assessment category and service life**
   In the impact category CC, the environmental effect of LLP replacements themselves is negligible compared to fuel consumption. However, in the impact category MM, the impact is more pronounced. Over a full engine lifecycle, the material related impact due to LLP replacement remains below one percent for intervals within 15,000–19,500 cycles, compared to the base interval. In contrast, shortening the service life to 12,000 cycles increases material consumption by up to two percents compared to an optimum replacement strategy. However, when LLPs have a high amount of remaining cycles (e.g. 8,000 cycles as in the LLP 12k replacement interval), reuse becomes more feasible, which again improves the overall resource efficiency.

2. **Cumulative waste of remaining LLP lifetime is significant**
   The majority of engines undergo LLP replacements around 15,000 cycles, leading to a substantial portion of the potential service life being discarded. This issue is particularly critical regarding material scarcity, as high-performance aerospace alloys depend on geopolitically sensitive supply chains, increasing the risk of supply chain disruptions and making material recycling an essential factor for long-term sustainability.

3. **Recycling strategies for aerospace materials are insufficient**
   Currently, aerospace materials are predominantly downcycled. This results in a significant loss of CRMs, which could otherwise be reintegrated into the aerospace supply chain. Advancing closed-loop recycling technologies — where high-performance alloys can be recovered and reintroduced into aviation-grade components — would improve both resource efficiency and supply chain resilience.

4. **Maintenance timing can significantly influence environmental performance**
   Minor adjustments in shop visit timing can optimize the interplay between engine degradation, performance restorations, and fuel efficiency. This can lead to a reduction in total environmental impact across all relevant categories. The results show that for shorter replacement intervals, such as a replacement after every 15,750 cycles, around 0.20% of the additional material-related impact (MM) is compensated by improved fuel performance (CC). It is imperative that further investigation is conducted into this interplay in order to analyze and comprehend detailed insights into the influence of different maintenance tasks on the overall environmental impact throughout the entire life cycle of engines. Future studies could also extend the analysis by considering the interplay between preventive maintenance intervals and the probability of unscheduled events, which may further influence the overall ecological impact of engine maintenance.

This paper has explored first insights into LLP replacement intervals and material criticality in aviation. It is the intention of the researchers to expand upon this exploration in future studies, refining and detailing these findings through additional simulations and research, such as economic factors, part reuse optimization, consideration of part repairs and transport phases as well as end-of-life recycling pathways. By continuing to examine these challenges, the researchers hope to contribute to more sustainable and resilient practices in aerospace maintenance and materials management.

NOMENCLATURE

CC	Climate Change
CRM	Critical Raw Material
EGT	Exhaust Gas Temperature
EFC	Engine Flight Cycle
FC	Flight Cycle
FH	Flight Hours
IAE	International Aero Engines
IAEG	International Aerospace Environmental Group
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LLP	Life Limited Part
MM	Resource Use - Minerals & Metals
MRO	Maintenance Repair and Overhaul
PR	Performance Restoration
RUL	Remaining Useful Life
SFC	Specific Fuel Consumption

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APPENDIX

Full set of LCIA results are available in the supplementary materials to this article.

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