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SUSTAINABILITY IN AVIATION: LIFE CYCLE ASSESSMENT OF COMPONENTS REPLACED IN

Sustainability in Aviation: Life Cycle Assessment of Replaced Components in Aircraft Maintenance

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SUMMARY:

Sustainability has become one of the main pillars of modern engineering, especially in sectors with high environmental impact such as aviation. This article proposes a scientific analysis on the life cycle assessment (LCA) of components replaced during aircraft maintenance, considering environmental, economic and regulatory aspects. LCA offers a systemic view of the environmental impacts throughout all phases of the component, from resource extraction to disposal. Based on academic references and technical reports up to 2023, the aim is to understand how the application of this method can assist in sustainable decision-making, optimizing resources and reducing the ecological footprint of the aeronautical industry.

Keywords: Sustainability; Aviation; Aircraft Maintenance; Life Cycle Assessment; Environmental Impact.

ABSTRACT:

Sustainability has emerged as one of the main pillars of modern engineering, especially in sectors with high environmental impact such as aviation. This article presents a scientific analysis of the Life Cycle Assessment (LCA) of components replaced during aircraft maintenance, considering environmental, economic, and regulatory aspects. LCA provides a systemic view of environmental impacts throughout all phases of a component's life, from resource extraction to final disposal. Based on academic references and technical reports up to 2023, the study seeks to understand how applying this method can support sustainable decision-making, optimize resource use, and reduce the ecological footprint of the aviation industry.

Keywords: Sustainability; Aviation; Aircraft Maintenance; Life Cycle Assessment; Environmental Impact.

1. INTRODUCTION

The aeronautical industry plays a central role in global mobility, contributing significantly to economic development while facing increasing environmental challenges. In a global scenario of climate warming, resource scarcity and pressure for more sustainable practices, aviation has sought to incorporate sustainability principles into its processes, including aircraft maintenance. In this context, the Life Cycle Assessment (LCA) of aeronautical components emerges as a tool

crucial scientific information for measuring and mitigating environmental impacts.

Replacing aircraft components is a routine practice, guided by safety and operational reliability standards. However, the disposal of these discarded components and the production of new parts have significant environmental repercussions, which are often overlooked in decision-making processes. LCA allows for a holistic understanding of the impacts from the extraction of raw materials to the end of the cycle, promoting an integrated view of sustainability in aeronautical engineering.

By integrating scientific LCA methods with aeronautical maintenance management, it is possible to propose solutions that involve reuse, recycling and innovation in materials, contributing to a less polluting and more efficient industry. Recent literature highlights the importance of considering the complete cycle of products to avoid the simple transfer of impacts from one phase to another (BAIRD; PLECASH, 2020; ISO, 2020).

This article will provide an in-depth discussion of six fundamental aspects of sustainability applied to the context of aircraft maintenance and LCA: theoretical foundations of LCA, current legislation and regulations, environmental impacts of replaced components, circular economy and reuse, analysis of case studies and technical challenges for the implementation of LCA in the sector. The conclusion proposes strategic guidelines for the definitive incorporation of sustainability in aircraft maintenance.

2 THEORETICAL BASES OF LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a scientific method standardized internationally by ISO 14040 and ISO 14044, which aims to identify, quantify and evaluate the environmental impacts associated with all stages of a product's life cycle, from the extraction of raw materials to final disposal. In the context of aviation, this tool is particularly valuable because complexity of the materials and processes involved in aircraft manufacturing and maintenance. LCA allows for a systemic view, avoiding specific solutions that merely transfer the environmental impact from one phase to another.

The LCA process consists of four main steps: definition of the objective and scope, inventory analysis, impact assessment and interpretation of results. The first step establishes the limits and objectives of the study, considering the specificities of the aeronautical component analyzed. In the second step, a systematic collection of input data is carried out and output (energy, water, emissions, waste, etc.). This data is then translated into impact categories such as climate change, toxicity, and resource use.

By applying LCA to aircraft component replacement, one gains the ability to compare material options, suppliers, and reuse or recycling strategies. For example, a study by Lee et al. (2021) demonstrated that reusing electronic components in aircraft can reduce COÿ emissions associated with the production of new parts by up to 37%.

LCA also makes it possible to identify environmental hotspots, i.e., stages of the life cycle with disproportionately high impacts. This allows for specific and optimized interventions, reducing costs and emissions simultaneously. In commercial aircraft, studies have identified that the maintenance phase represents around 20% of the emissions associated with the complete life cycle of the aircraft (IATA, 2022).

Another important point is the growing integration of LCA with environmental management tools such as Design for Environment (DfE) and Life Cycle Cost Analysis (LCC). The synergy between these approaches provides a more robust framework for sustainable and economically viable decision-making, especially when combined with computational modeling.

Finally, it is essential to highlight that the effective application of LCA requires a consistent, up-to-date database that is representative of the local reality. Databases such as Ecoinvent, Gabi and the Brazilian Life Cycle Inventories have been essential to ensure the reliability of studies, allowing comparability and standardization between different components and scenarios.

3 LEGISLATION AND REGULATIONS ON SUSTAINABILITY IN AVIATION

Environmental regulation in aviation has undergone significant changes over the last few decades, especially in light of growing concerns about greenhouse gas emissions and the disposal of technological waste.

To ensure that sustainability is effectively integrated into the sector, several international organizations and national authorities have been establishing guidelines and regulations that directly influence the maintenance, disposal and reuse practices of aeronautical components.

The International Civil Aviation Organization (ICAO) has played a key role in standardizing sustainable policies in the global aviation sector.

Through the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) program, launched in 2016, signatory States commit to carbon neutralization targets in international operations, requiring airlines to be more transparent in their environmental processes and reports (ICAO, 2019).

At the European level, the European Aviation Safety Agency (EASA) has incorporated environmental guidelines into its technical regulations, requiring, for example, that manufacturers of aircraft submit environmental impact reports for critical components. This directly affects maintenance by encouraging replacement with recyclable parts or those with a lower environmental burden (EASA, 2020).

In Brazil, ANAC (National Civil Aviation Agency) has also started to integrate environmental criteria into its technical regulations. Resolution No. 457/2018 introduced eco-efficiency principles into maintenance operations and suggested practices such as proper management of hazardous solid waste, traceability of parts and encouragement of component reuse whenever possible. The National Solid Waste Policy (Law No. 12,305/2010) is another fundamental instrument, imposing shared responsibility for the life cycle of Products.

These regulations represent a technical and logistical challenge, as they require the aviation supply chain to fully track components from their manufacture to their final disposal. This imposes a new paradigm on companies in the sector, which now require computerized lifecycle management (PLM) systems and greater integration between the engineering, maintenance and sustainability sectors.

Despite the progress, there are still significant gaps, especially regarding the international standardization of LCA data. While ISO 14044 defines general parameters, the lack of specific methodologies for the aeronautical sector makes comparisons and rapid decision-making difficult. Initiatives such as SAE International's Aerospace Environmental Strategy Group (AESG) have sought to fill this gap by developing methodologies adapted to the reality of aircraft and their operational cycles.

Therefore, environmental legislation in aviation is moving towards a more rigid model, integrating environmental responsibility into the complete life cycle of aeronautical products. As a result, LCA is gaining ground as an essential tool for complying with current regulations and for building a more sustainable industry that is resilient to future climate challenges.

4 ENVIRONMENTAL IMPACTS OF REPLACED COMPONENTS

The replacement of components in aircraft, although essential to ensure the safety and performance of air operations, represents a critical point in terms of environmental impacts. Each part removed from the production system requires a production chain for replacement and, often, an inadequate destination, intensifying problems such as excessive consumption of natural resources, greenhouse gas emissions and accumulation of solid waste. Understanding the environmental impact of replaced aeronautical components is essential to support sustainable policies and guide technical and logistical decisions in the sector.

In general, aeronautical components are manufactured with high-tech materials, such as special metal alloys, carbon composites and sensitive electronic elements, whose production requires energy-intensive industrial processes with high polluting potential. A study conducted by Ahmad and Kumar (2022) showed that the production of certain sensors used in

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Air navigation systems generate, on average, 5.3 kg of COÿ equivalent per unit, in addition to toxic waste from the use of heavy metals. These numbers become even more relevant when considering the high turnover of components in commercial aircraft, which undergo frequent predictive and corrective maintenance cycles.

In addition to production, improper disposal of these materials worsens environmental impacts. Many discarded components end up in industrial landfills or are exported to countries with less stringent environmental standards, as pointed out by Hossain and Rahman (2021), who identified an 18% increase in the volume of aeronautical waste sent to Southeast Asian countries in the last decade. The lack of standardized recycling and reuse policies increases environmental liabilities and poses risks to public health, soil, and groundwater.

On the other hand, reuse and reconditioning of components have demonstrated results promising in mitigating these impacts. In a Boeing case study (2020), the implementation of remanufacturing processes in aircraft turbines resulted in an annual saving of 2,000 tons of COÿ and a 25% reduction in the extraction of specific metal alloys.
This practice, in addition to being environmentally viable, reduces operating costs and increases industry competitiveness.

The Life Cycle Assessment (LCA) of replaced components enables the precise quantification of these impacts, providing technical support for process improvement and the development of sustainability policies.

When applied systematically, LCA identifies critical points in the value chain, such as the origin of materials, machining processes, transportation and final disposal, allowing for more effective interventions. This approach also strengthens component traceability, contributing to a more efficient and transparent maintenance system.

Finally, it is essential that the industry invests in research and innovation aimed at producing more sustainable components, with a lower environmental burden and greater reusability. Emerging technologies such as 3D printing with recyclable materials, biocomposites and biodegradable sensors are emerging as promising alternatives. The articulation between universities, manufacturers, airlines and regulatory bodies will be essential to foster these solutions and integrate them into the daily life of aviation, promoting a true ecological transformation in the sector.

5 CIRCULAR ECONOMY AND REUSE OF COMPONENTS AERONAUTICAL

The circular economy represents an alternative production model to the traditional linear system, proposing the reuse, reconditioning and recycling of materials to extend their life cycle as much as possible. In the aeronautical sector, this approach gains special relevance given the complexity and high cost of components, as well as the growing pressure for sustainability. Incorporating circular economy practices into aircraft maintenance has proven to be strategic from both an environmental and economic point of view. Adopting the circular economy involves transforming the way components are designed, manufactured and managed throughout their useful life.

This means, for example, developing parts that are more easily disassembled, repairable and recyclable, as well as implementing traceability and logistics return policies. A successful example of this application is Airbus's "Used Serviceable Material" program, which reuses parts in good condition from decommissioned aircraft, reducing the demand for new materials and the environmental impact of the supply chain (Airbus, 2022).

In the context of aircraft maintenance, the reuse of components is subject to strict safety and quality criteria. Parts such as brakes, turbines, hydraulic systems and navigation instruments can be reconditioned and certified for new use, as long as they meet the requirements of regulatory agencies such as the FAA and EASA. According to a report by IATA (2021), approximately 60% of parts removed from decommissioned aircraft can be safely reused or recycled, which represents enormous potential for reducing costs and emissions.

The circular economy also encourages the emergence of new business models, such as component leasing, in which ownership of the parts remains with the manufacturer or supplier, who is responsible for their maintenance and replacement. This creates incentives for the production of more durable and recyclable parts, aligning economic and environmental interests. It is estimated that the global market for reused aeronautical parts generates more than US$ 3 billion per year (Oliver Wyman, 2022), reflecting the growth and viability of this segment.

For the circular economy to be fully implemented in aviation, it is essential to invest in technologies that facilitate the disassembly and diagnosis of components. Tools such as reverse engineering, 3D printing and intelligent RFID tracking systems make the separation of materials and the reintegration of parts into the production system more efficient. In addition, partnerships between manufacturers, airlines and maintenance centers have proven to be essential for sharing knowledge and logistics infrastructure. However, significant challenges remain, such as standardization of processes, cultural resistance to the reuse of components, and the lack of fiscal and regulatory incentives in many countries. Overcoming these barriers requires coordinated action between the public and private sectors, in addition to the technical training of the professionals involved. Promoting the circular economy in aviation should not be seen as just an option, but as an urgent need in view of global environmental commitments and the scarcity of natural resources.

6 LOGISTICAL AND OPERATIONAL CHALLENGES IN SUSTAINABLE MANAGEMENT OF AERONAUTICAL PARTS

The sustainable management of aeronautical parts faces a series of logistical and operational challenges that directly impact the efficiency and effectiveness of environmental strategies in the sector. The complexity of the supply chain, combined with the rigidity of safety and quality requirements, makes the process of replacing, reusing and discarding components an exercise in balance between technical performance and ecological responsibility. With the globalization of operations, the challenges increase, requiring coordination between various actors, from manufacturers to logistics operators and regulatory bodies.

One of the main logistical obstacles lies in the traceability of components throughout their life cycle. Without an effective monitoring and control system, it becomes difficult to accurately assess the origin, condition, and destination of replaced parts. Technologies such as blockchain, RFID, and artificial intelligence have been proposed as promising solutions to increase the transparency and integrity of logistics data. Studies such as that by Lee et al. (2021) highlight that the adoption of blockchain in aeronautical parts management systems can reduce losses and logistics errors by up to 30%.

Another relevant challenge is coordination between maintenance centers, airlines, and suppliers to ensure reconditioning and reverse logistics of components. Often, the lack of standardized contracts and adequate infrastructure hinders the efficient flow of reusable parts, resulting in material losses and increased waste. As reported by Souza and Andrade (2020), approximately 22% of the parts discarded by Latin American companies could have been reused if there had been a more integrated logistics chain.

Furthermore, the geography of aeronautical operations requires tailored logistics solutions. In countries with large territorial extensions or limited infrastructure, such as Brazil, the movement of reusable parts between different regions presents high costs and deadlines that are incompatible with operational demand. This reinforces the importance of regional logistics hubs and the adoption of more sustainable transport technologies. The proposal to use cargo drones for urgent deliveries of parts, for example, has been tested at remote airports in Asia and Africa with positive results (IATA, 2021).

From an operational point of view, professionals involved in aircraft maintenance also face challenges related to technical training and the standardization of sustainable processes. The introduction of environmental criteria into maintenance decisions requires specific training, updated manuals and integration between engineering and sustainability teams. According to Oliveira and Ribeiro (2023), 65% of maintenance centers certified by ANAC have not yet incorporate environmental metrics into their operational protocols.

Finally, the initial costs of adapting infrastructure, purchasing technologies and training represent significant barriers, especially for small and medium-sized companies. Although the return on investment is proven to be positive in the long term, according to a study by ICAO (2022), government support, through tax incentives and subsidies, is essential to enable the sustainable transition. Overcoming these logistical and operational challenges is a fundamental condition for consolidating environmentally responsible, safe and economically viable aviation in the 21st century.

7 FUTURE PERSPECTIVES AND SUSTAINABLE INNOVATIONS IN THE SECTOR

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Sustainability in the aviation sector requires constant innovation and adaptation in the face of environmental challenges and the demands of global aviation. With the advancement of technologies and the intensification of decarbonization goals imposed by international organizations such as ICAO and IATA, new perspectives emerge to promote greener aviation. Technological innovations, paradigm shifts in aircraft production and maintenance, as well as the strengthening of public policies focused on sustainability, are fundamental vectors of this transformation.

One of the biggest highlights among sustainable innovations is the development of electric and hybrid aircraft, which promise to significantly reduce COÿ emissions in the coming decades. Projects such as Eviation's Alice and Airbus' EcoPulse are testing the technical and economic feasibility of fully electric flights on regional routes. Although challenges remain significant, especially in terms of range and charging infrastructure, these aircraft represent a promising break with the traditional fossil fuel-based model.

Another impactful innovation is the increasing use of sustainable aviation biofuels (SAF – Sustainable Aviation Fuel), which have the potential to reduce greenhouse gas emissions by up to 80% over their life cycle, according to data from IATA (2021). Investment in technologies for producing SAF from organic waste, used oils and lignocellulosic biomass has been gaining ground in research centers and among major manufacturers.
It is predicted that, by 2050, around 65% of the sector's total emissions reduction will come from the use of SAF (ICAO, 2022).

In the field of maintenance and component management, digitalization and the use of artificial intelligence offer possibilities for predictive monitoring and resource optimization. Smart sensors attached to critical parts allow for early detection of failures, reducing unnecessary interventions and extending the useful life of components. Integrating this data into machine learning-based platforms allows for maintenance planning with greater energy efficiency and less waste of parts, contributing to a more sustainable supply chain.

Furthermore, 3D printing has revolutionized the manufacturing of aeronautical parts, enabling on-demand production with less material and lower energy consumption. General Electric, for example, uses additive manufacturing to produce injector nozzles for turbines, reducing the weight of the parts by 25% and the consumption of raw materials by 30% (GE Reports, 2021). This technology also facilitates the reuse of recycled materials in the manufacture of new parts, in line with the logic of the circular economy.

Future prospects also involve changes in regulatory and institutional models. International standardization of environmental standards, the creation of green labels for air operators and the requirement for detailed environmental impact reports should become mandatory practices.
Government support for startups and universities focused on sustainable innovation in aviation

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is also essential. Initiatives such as Clean Sky 2, funded by the European Union, demonstrate how the combination of public and private resources can accelerate this transition.

Therefore, the future of sustainability in aviation will depend on the combination of technological innovation, reconfiguration of production and maintenance models, effective public policies and awareness among all stakeholders. By integrating these fronts, the sector will be able to move towards a carbon-neutral aviation, more efficient and committed to future generations.

Conclusion

Sustainability in aviation, especially with regard to assessing the life cycle of components replaced during maintenance, is emerging as one of the greatest challenges and, at the same time, one of the greatest opportunities for the sector. A detailed study of each stage of the life cycle – from manufacturing to disposal or reuse – reveals not only the environmental impacts associated with aeronautical operations, but also opens up space for technological innovation, the rationalization of logistics processes and the adoption of more sustainable production models.

The analysis showed that replaced components account for a significant portion of aviation's environmental footprint, requiring new approaches to waste management, reuse and refurbishment of parts. Technologies such as 3D printing, smart sensors, biofuels and blockchain have the potential to transform current practices, bringing the sector more in line with global emissions reduction and energy efficiency targets.

In addition to technical advances, there is a need for more integrated environmental governance, involving manufacturers, operators, maintenance centers and regulatory bodies around common objectives. Strengthening the circular economy, standardizing processes and encouraging innovation are fundamental pillars for consolidating sustainable practices across all sectors. the links in the chain. Another point of attention is the qualification of the professionals involved, who must be trained not only technically, but also environmentally. Sustainability needs to be understood as an essential competence in the aeronautical sector, permeating strategic, operational and technical decisions. This will make it possible to create an organizational culture committed to environmental preservation and operational excellence.

The transition to more sustainable aviation is not a simple or immediate process, but rather an ongoing process that requires investment, research, and cooperation between different sectors of society. By recognizing the impacts of replaced components and proposing innovative and sustainable ways to manage them, this article contributes to the scientific and practical debate on the direction of aviation in the 21st century.

Therefore, it is possible to state that sustainability in aviation depends on the synergy between technology, logistics, regulation and organizational culture. Based on an assessment model

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of the life cycle, the sector will be able to make more informed and effective decisions, promoting aviation that respects the environment, operational safety and future generations.

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