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NEW TECHNOLOGIES IN AVIATION – A FACTOR IN ECONOMIC AND ENVIRONMENTAL EFFICIENCY

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Abstract: *This study analyzes how technological innovations in aviation affect passenger comfort, flight safety, and environmental performance. The focus is placed on key innovative technological solutions in modern aircraft manufacturing, particularly the increasing use of composite materials in aircraft structures. A quantitative assessment of life-cycle carbon emissions associated with composite-based aircraft is carried out using the Life Cycle Assessment (LCA) methodology in accordance with European standards. The analysis examines carbon emissions at each stage of the aircraft life cycle and evaluates the economic and environmental impact of composite materials, from raw material production to end-of-life recycling. In addition, the influence of new aviation manufacturing technologies on fuel consumption, passenger safety and comfort, and operational characteristics is considered. The results are presented graphically and serve as a basis for conclusions regarding the economic and environmental effects of composite material use. Alternatives are suggested for addressing the environmental challenges arising from the introduction of new aviation manufacturing technologies using composite materials, in accordance with European environmental standards, without adversely affecting the ever-growing needs of the aviation industry, including those of passengers.*

Keywords: technological innovations, composite materials, aircraft structures, carbon footprint, environmental impact

1. Introduction

The development of modern aircraft structures is driven by increasing technical, operational, economic, and social requirements. Manufacturers need to consider passenger comfort and safety, reduce carbon emissions to meet environmental standards, and lower the cost of travel amid rising energy prices, i.e., improve the efficiency of air transport. This requires the use of new innovative technological solutions in modern aircraft construction. New construction materials, particularly composites, are being used on an increasingly large scale, as they combine properties that are not achievable with traditionally used metals and alloys. Recent technological developments indicate a continuous increase in the share of composite materials (CFRP - carbon fiber reinforced polymer) used in modern passenger aircraft structures. A comparative analysis of older and newer, more modern aircraft designs shows a steady increase in the use of composite materials for the manufacture of aircraft structural components. Statistical data indicate that the proportion of composite materials in Airbus commercial aircraft has increased from approximately 5% in the early 1970s to over 50% in recent models.

Over the past 60 years, the share of composites in Boeing aircraft structures has increased from about 5–10% in the Boeing 737 to over 50% in the Boeing 787, with CFRP being used primarily for the wings and fuselage. [7, 8]. (Figure 1)

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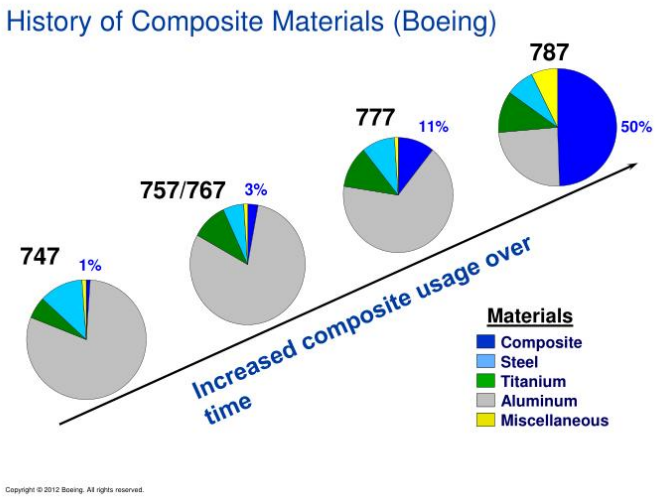


Figure 1: Increase in the share of composite materials in the structure of Boeing civil aircraft (1960–2020).
Source: Boeing, 2020, Current Market Outlook; Adapted from: R. Matthews, "Advanced Composites in Aerospace," Journal of Composite Materials, 2018.

This enables the implementation of fundamentally new design solutions and technological processes. The required physical and mechanical characteristics are achieved through optimized selection of components and controlled mutual arrangement of reinforcing elements during technological forming. New materials with improved characteristics and automated processing capabilities enable a real reduction in weight, increased strength, lower operating costs, and increased payload for CFRP aircraft compared to their metal counterparts.
In this way, new technologies are becoming a major driving force in the development of society. Their influence is evident in various aspects of human life: education, communication, politics, work, and transportation. Technologies are an integral part of modern life, and their impact on human development is undeniable [6]. They are also an integral part of the development of modern aviation. These technological developments have contributed to improvements in the efficiency and safety of air transport. Such progress can be observed in the introduction of electric and hybrid aircraft that reduce carbon emissions, as well as in the use of advanced systems for safe and efficient air traffic management across the full range of altitudes and speeds. In addition, the introduction of advanced GPS systems and automated flight control systems contributes to more accurate and safer navigation of aircraft [1]. In the search for solutions to the problems of reducing operating costs, reducing harmful emissions, and improving comfort and microclimate during travel, aviation manufacturers are developing and implementing new construction materials. The new construction materials are lighter, stronger, cheaper, and generally more technologically advanced. They improve the economy and efficiency of aircraft engines and enable the design and development of fundamentally new aircraft—electric and hybrid aircraft—guided by the principle of "safety first" [3]. Technological innovations in the aviation industry can be divided into several main areas:

- Use of new construction materials
- Creation and use of new fuels
- Increasing the efficiency of aviation gas turbine engines
- Digital and software know-how

And here the question arises: to what extent and in what "direction" does the development and implementation of new materials, engines, and concepts affect the economic, environmental, and human

spheres of life? In search of an answer to this question, the article analyzes and compares the effect of using new construction materials in several areas of human activity: ecology, economic aspects as well as comfort and microclimate when traveling.

What are the new construction materials? Composite materials, especially CFRP (Carbon Fiber Reinforced Polymer) materials, offer: greater specific strength, lower weight, improved corrosion resistance, and most importantly, they withstand the complex operational loads of aircraft structures very well. The mechanical response of these materials under load is governed by their anisotropic microstructure, in which load-bearing fibers are embedded within a polymer matrix that redistributes stresses. This makes them suitable for manufacturing key structural elements of aircraft, such as wings, center wing elements, and body parts [9]. The effect of this is primarily a reduction in aircraft weight (by about 30%), which in turn leads to reduced fuel consumption and increased flight duration. However, they also have disadvantages—under high cyclic loads (during flight), composites develop microscopic defects that grow over time and manifest as cracks in the matrix, delamination, etc. Their long-term performance under cyclic loading, vibration, and fatigue remains an active area of engineering research. [14]. (Figure 2)

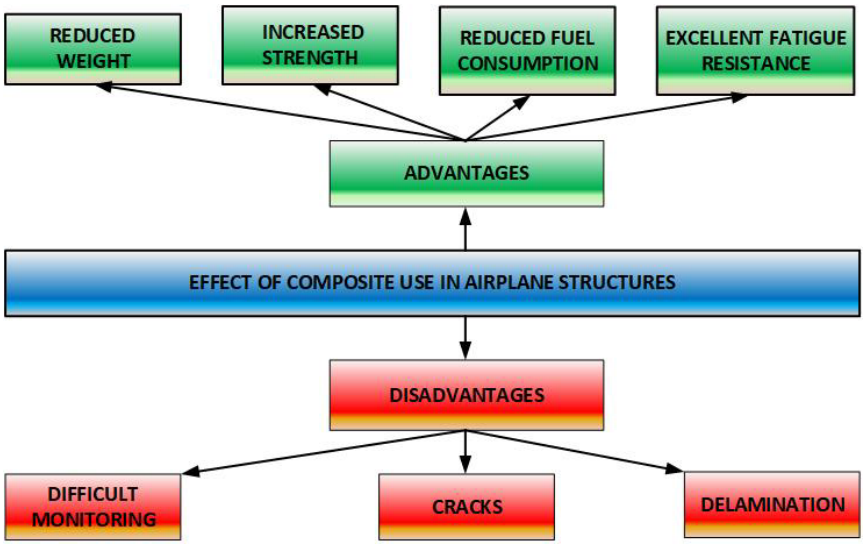


Figure 2: Strength and weight effect of using CFRP composites in aircraft construction

2. Methodology

This section presents the methodological approach used to analyze the impact of technological innovations in aviation on economic and environmental performance. In this context, the study is based on a review of peer-reviewed scientific publications, official reports by ICAO, EASA, and IATA, and a comparative analysis of quantitative indicators such as fuel consumption, CO_2 emissions, and noise. [1-4]. The analysis focuses on key technological solutions in modern aircraft manufacturing, particularly the increasingly widespread use of composite materials. Specifically, it examines the economic and environmental impact of their application in aviation structures. The economic and environmental advantages and disadvantages are examined across all stages of the product life cycle, from raw material production to end-of-life recycling. To a certain extent, the impact of new materials on the safety, comfort, and operational characteristics of passenger aircraft is taken into account. The environmental impact of composite-based aircraft structures is quantified using a Life

Cycle Assessment (LCA) methodology in accordance with ISO 14040:2006 [5] (Figure 3).

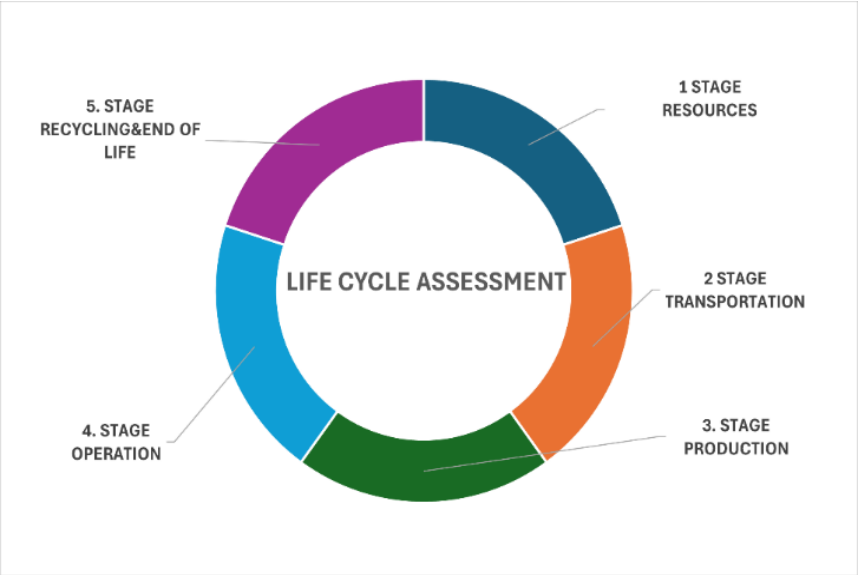


Figure 3: Algorithm for analyzing the entire life cycle of technical products

Based on the results obtained and quantitative indicators, relevant conclusions and findings are formulated. Based on the principles laid down in the LCA methodology, the benefits and potential negative effects of using composite materials in aircraft structures are evaluated across the following stages: raw material extraction and procurement, transport, part manufacturing, operational cycle, and recycling. A comprehensive comparative economic and environmental assessment was conducted based on these criteria. The economic and environmental aspects of each stage of the life cycle of composite products are examined.

The presented assessment is comparative in nature and is intended to illustrate general life-cycle trends rather than provide a fully parameterized industrial model.

The analysis and processing of the available statistical data show the following results:

- Raw material extraction and material procurement, component manufacturing

The most commonly used composite materials for manufacturing aircraft structural components are CFRP (carbon fiber reinforced polymers). These materials provide high strength at a low relative weight. Compared to standard aluminum alloys, the production of composite materials is significantly more energy-intensive, resulting in a higher carbon footprint than aluminum alloy production.

Analysis of available statistical data indicates that the production of 1 kg of composite material emits approximately 20–30 kg of CO_2, whereas the production of 1 kg of aluminum alloy emits approximately 8–16 kg of CO_2 [10].

The large difference in carbon emissions during the material extraction stage is due to the high energy costs of producing carbon fibers. For example, if an aluminum panel weighing 100 kg is manufactured for a given structure, its production results in approximately 1,000 kg of CO_2 emissions (assuming an average of 10 kg CO_2e/kg). If the same panel is produced from composite material, its weight would be approximately 70 kg, resulting in around 1,435 kg of CO_2 emissions (assuming an average of 25 kg CO_2e/kg). Such weight values are representative for large fuselage and wing panels in passenger and transport aircraft.

- Operation

In the operation of aircraft structures, the effect of using composite materials manifests itself in two aspects: environmental and economic.

The primary environmental benefit arises from structural weight reduction enabled by composite materials. Compared to equivalent structures made of standard aluminum and other light metal alloys, composite structures typically weigh 20% to 50% less [11,12]. Weight reduction directly decreases fuel consumption—by up to 20% under comparable operational conditions—and proportionally reduces life-cycle carbon emissions. Figures 4 and 5 show illustrative estimates of the total amount of carbon emissions released into the atmosphere over the entire life cycle of an aircraft, using composite materials (CFRP) in the structure and a standard metal (aluminum alloy) structure.

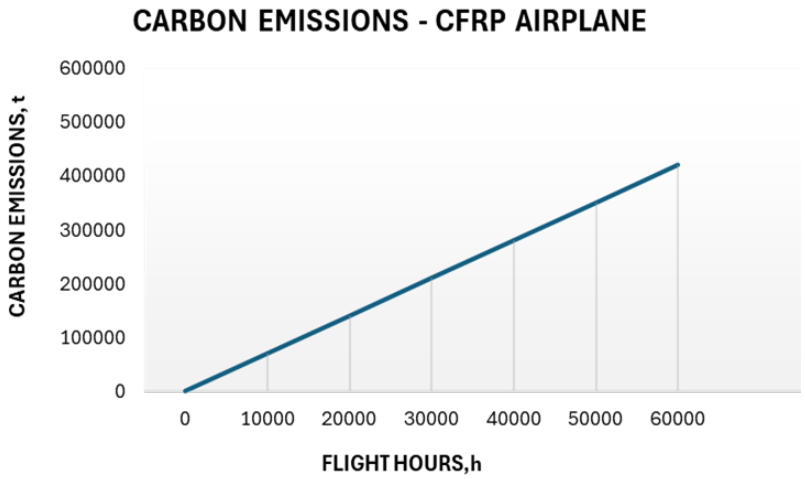


Figure 4: Total carbon emissions released into the atmosphere over the entire life cycle of a passenger aircraft using composite materials in its construction

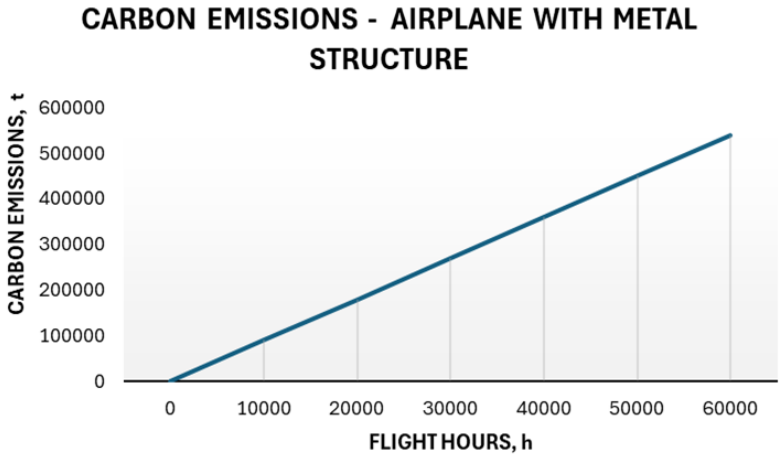


Figure 5: Total amount of carbon emissions released into the atmosphere over the entire life cycle of an average passenger aircraft with a conventional metal structure

The graphs show the total amount of emissions accumulated in the atmosphere over the entire life cycle (according to the LCA methodology) of an average passenger aircraft using composite materials in its construction and an aircraft with a standard metal construction.

The economic benefits of weight reduction result from reduced fuel costs. Over tens of thousands of flight hours, the cumulative fuel savings associated with reduced structural weight may amount to several million dollars per aircraft. Lower structural weight also reduces mechanical stress on engines and primary structural components, contributing to lower operating costs for maintenance, spare parts, and repairs.

- Maintenance and repair

During operation and routine maintenance, components made of composite materials demonstrate high corrosion resistance, strong vibration resistance, and high material fatigue strength. These properties allow for extended inspection intervals and may reduce the frequency of repairs. At the same time, the repair of such components requires specialized equipment and specific repair technologies, which are more expensive than those used for traditional metal structures. Over the operational life cycle, composite-intensive aircraft exhibit reduced maintenance costs [12]. Indirectly, new technologies related to the use of composite materials in aircraft construction also bring benefits to the environment. The reduction in the volume of repair work leads to reduced waste generation, fewer spare parts, lower transport costs, etc., which positively influences environmental performance.

- Recycling

The final stage of the product life cycle, according to the LCA methodology, is end-of-life and recycling. At the end-of-life stage, composite materials present several challenges. Recycling remains complex, as fully developed and widely implemented technologies for separating carbon fibers and braid from the polymer matrix are still limited. Consequently, CFRP recycling represents both a technological and economic challenge, as current recycling technologies remain more energy-intensive and technologically complex than established aluminum recycling processes. According to [13,14], the cost of recycling one ton of composite materials ranges from 500 to 2000 euros, which represents a relatively high cost. One possible approach to addressing this issue is the development of technologies for the secondary use of CFRP components in less load-intensive structural applications. Expensive recycling technologies for composite materials generally increase overall processing costs and result in a larger carbon footprint at the final stage of the life cycle of such components compared to equivalent components made from standard aluminum alloys.

3. Conclusions

The use of new technologies in aircraft manufacturing leads to a reduction in carbon footprint, improved passenger comfort, and enhanced flight safety. In this respect, technological developments in aviation have a significant economic and environmental impact. The introduction of new materials increases the service life of aircraft, improves corrosion resistance, and reduces fuel consumption.

As shown by the analysis of the different stages of the life cycle, the environmental and economic impact of using composite materials varies depending on the stage considered. The total amount of carbon emissions released throughout the life cycle of an aircraft using composite materials, compared to an aircraft with a conventional aluminum alloy structure, is illustrated in Figure 6.

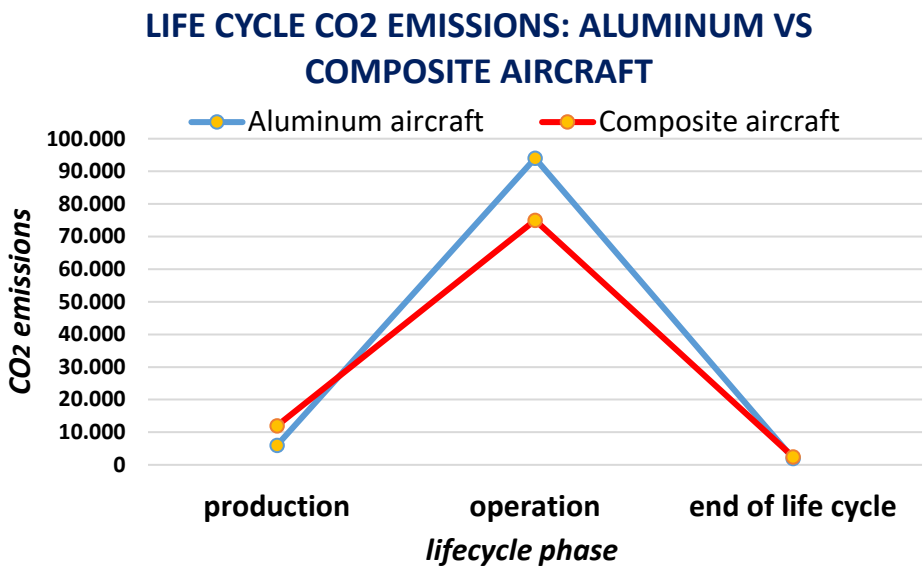


Figure 6: Life cycle carbon emissions: Aluminum vs Composite structure aircraft

The analysis shows that the use of composite materials in aircraft construction leads to a reduction in the carbon footprint, particularly during the operational phase. To achieve long-term sustainability in this process, it is necessary to implement a comprehensive set of technological and organizational solutions that reduce the carbon footprint throughout the entire life cycle of aircraft. New approaches and technological solutions are needed, such as:

- new generations of highly efficient aircraft engines

Particularly promising are geared turbofan engines, hydrogen fuel systems, and hybrid-electric propulsion systems. The latter are viewed as a transitional technology toward the full electrification of aircraft. Development of electric and hybrid aircraft are seen as a transitional step towards fully electric aircraft, with the aim of significantly reducing carbon emissions. The new concepts also require fundamentally new power plants and propulsion systems, but without compromising passenger safety and comfort.

- new aviation fuels

The use of sustainable aviation fuels (SAF). According to the literature, the use of SAF can reduce carbon emissions from aircraft by up to 80%, while still using standard aircraft engines.

- new structural materials

The development and implementation of new structural materials, such as composite materials. Given the high carbon footprint of the production and recycling stages, it is essential to develop new technologies for recycling composites, such as pyrolysis, solvolysis, and mechanical shredding, followed by the reuse of fibers in secondary structures or non-critical components. For example, the "design for disassembly" concept allows for easier disassembly and separation of materials at the end of their life cycle.

- life cycle optimization

Another important area is comprehensive life cycle optimization (Life Cycle Assessment – LCA) through computer simulations and structural health monitoring. This enables the preventive assessment of technical condition, a reduction in the volume of repair work, and an extension of the service life of components.

Ultimately, addressing the issue of carbon emissions from aircraft requires a comprehensive approach. This approach combines innovations in manufacturing technologies, new fuels, new structural materials, and effective management of the entire aircraft life cycle.

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