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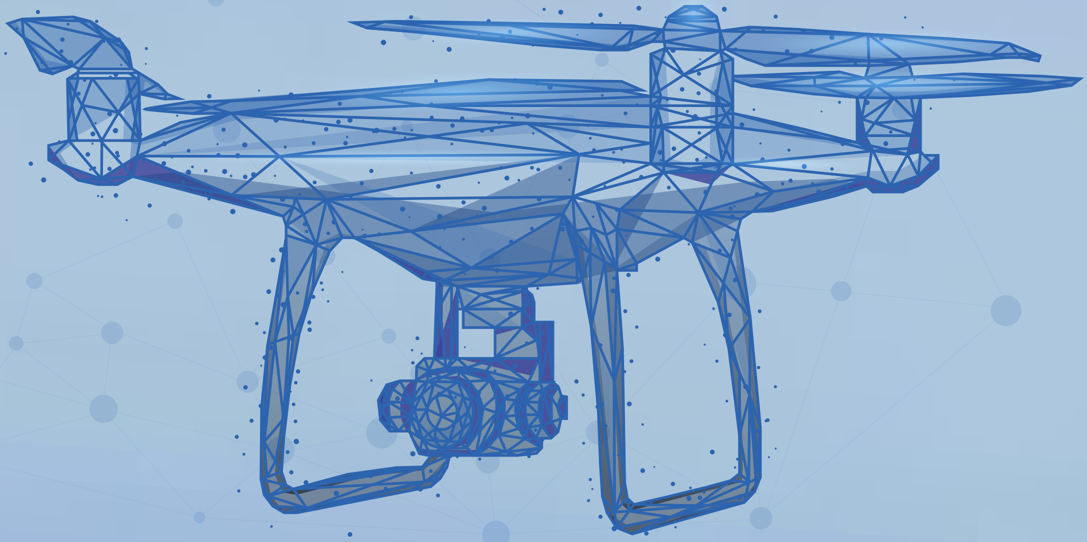

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Research Article

Modification of the Regulatory Framework for Aircraft with e-VTOL Capabilities

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Abstract

This paper analyzes the legal dimensions and regulatory framework of e-VTOL aircraft, providing a comprehensive review of the modifications and adaptations of legislation, while emphasizing the current status and integration issues within urban air transportation systems. Primary focal points encompass the progress, execution, and challenges of regulations established by the FAA, EASA, and state authorities concerning electric vertical takeoff and landing (e-VTOL) aircraft, which are critical for urban air mobility operations in metropolitan setting. These advancements must be incorporated into the urban regulatory framework, encompassing current aviation regulations and the imperative to establish new policies tailored for urban aerial transportation. This study delineates a framework and an extensive overview of regulations for diverse stakeholders, including the aviation sector, policymakers, and urban planners, emphasizing the necessity for a profound comprehension of regulations and the potential of UAM for effective integration into urban mobility systems.

Keywords

Regulation
Legal Framework
e-VTOL
Urban Air Mobility

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1. Introduction

Advanced Air Mobility (AAM) refers to a new concept of air transportation that represents a transformative change in the aerospace industry, enabling new capabilities and applications. AAM systems incorporate next-generation transport, including remotely piloted, autonomous, or vertical takeoff and landing (VTOL) aircraft powered by electric or hybrid-electric propulsion. An electric vertical takeoff and landing (e-VTOL) aircraft is designed to move people and cargo between places not easily served by surface transportation or existing aviation modes. AAM is poised to significantly impact Urban Air Mobility (UAM) by leveraging Enhanced Accessibility and Reduced Travel Time, with Environmental Benefits and Economic Growth, as well as ensuring Safety and Security of air travellers following to airworthiness requirements (Arco et al., 2023).

Electric vertical take-off and landing (e-VTOL) aircraft, as a swiftly flowing technology at the intersection of innovation, sustainability, and changing transportation requirements, are set to transform the aviation sector. This novel lightweight aircraft uses electric power for vertical take-off, hovering, and landing and has become essential in meeting contemporary urban transportation demands. eVTOLs provide an eco-friendly transportation alternative for transporting passengers and freight in metropolitan environments up to 500 km, mitigating ground transit congestion and decreasing carbon emissions. Commercial e-VTOL operations startups Joby and Archer Aviation are expected to commence air taxi networks in 2025 (Bellan, 2024).

Although e-VTOL technology has been conceptualized

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for over a decade, advancements and investments in the area have markedly intensified in recent years. Progress in electric battery technology and an increasing desire for sustainable transportation have stimulated interest in e-VTOLs across several sectors, including aviation, automotive firms, technological start-ups, and early-stage investors. The augmented prospects in e-VTOLs are integral to the transportation sector's emphasis on advanced air mobility, which seeks to modernize and optimize the conveyance of individuals and goods within regional and urban networks. Within AAM, e-VTOLs are anticipated to be pivotal in urban air mobility, the developing paradigm for air transportation at reduced altitudes within and between metropolitan areas. The e-VTOL business is evolving swiftly, with numerous companies engaging in collaborative ventures for innovative e-VTOL designs and infrastructure, such as fleet operation, vertiports, air traffic management, and maintenance in pursuit of commercial applications.

Numerous e-VTOL classifications exist, each with distinct design architectures, battery power concepts, and flight performance options (VFS, 2024). EASA (2019) has evaluated around 150 distinct e-VTOLs to facilitate equitable certification for various urban air vehicles, as outlined in document SC-VTOL-01. Thus, the differentiation of e-VTOL projects offers a competitive edge in market accessibility, while also presenting several disadvantages related to maintenance, operational costs, and expenditures. The maintenance organization and associated processes in the aviation sector are founded on a series of procedures derived from legislation and management decisions established by common international regulations, including the International Civil Aviation Organization (ICAO), European Union Aviation Safety Agency (EASA), Federal Aviation Administration (FAA) of the United States, and local civil aviation authorities (CAA). Conventional aircraft maintenance depends on manufacturer maintenance planning documents (MPD) sanctioned by the aviation authorities of the operating countries. The maintenance program (MP) encompasses four distinct types of checks (A, B, C, and D) categorized as line and base maintenance (Sriram and Haghani, 2003), along with the execution of changes, alterations, and AD/SB in accordance with manufacturer directives. All inspections concentrated on evaluating aircraft systems and essential components based on flight hours and cycles, occasionally employing calendar intervals (Bugaj et al., 2019; Sanchez et al., 2020). In the implementation of urban air mobility (UAM) operations, it is essential to adopt a maintenance and engineering strategy that schedules repair activities based on aircraft usage and demand projections.

Maintenance, Repair, Overhaul (MRO) is a crucial infrastructure in the aviation industry, serving as an organization that guarantees operational safety and upholds the reliability of urban air vehicles through a manufacturer-mandated maintenance program (Liu et al., 2019). The designated maintenance servicing team at vertiport line stations will conduct pre-flight checks, visual inspections, battery charging for air vehicles, and minor airframe and avionics system assessments for release to service (CRS), all while adhering to the flight schedule and facilitating operational efficiency. As air mobility matures, base maintenance inspections must be conducted on a substantial fleet of aircraft at authorized MRO facilities for specific vehicle types.

The aviation sector is experiencing a shortage of technical personnel, and the introduction of e-VTOL aircraft is anticipated to exacerbate the issue. As the UAM market evolves, aviation will transform, necessitating the adaptation of certification for maintenance workers specializing in advanced air mobility (AAM) aircraft types, including avionics-electrical and aircraft powerplant technicians/mechanics, as well as aircraft maintenance engineers. Prior to the acquisition of type certification for e-VTOL aircraft, the maintenance framework and MRO activities were undefined (Noble, 2023); nevertheless, the requisite skills and prevailing regulations for maintenance procedures will align with Part-145, as established by either the FAA or EASA (Roger, 2023). The present research is proposing a future-oriented MRO framework compliant with Part-145 regulations for maintenance activities with e-VTOL aircraft.

Final regulations for the introduction of Innovative Air Mobility (IAM), which includes air taxi services, have been established by the European Commission through the adoption of a set of secondary laws pertaining to drones and VTOL capable aircraft. This package is based on the EASA's (European Aviation Safety Agency) legislative suggestions, which were released in August 2023 in Opinion No. 03/2023. All areas of Air Operations (Air OPS), Flight Crew Licensing (FCL), Standardized European Rules of the Air (SERA), and Air Traffic Management (ATM) are covered by the new regulations that govern piloted electric air taxis. Additionally, it lays out procedures and standards for the certification and upkeep of unmanned aerial vehicles. With this package and other pieces of legislation already in place, air taxi services can finally take off. Additionally, in order for air taxis to start operating in Europe, certification from the European Aviation Safety Agency (EASA, 2024) is necessary.

Additionally, technological integration, including automation and artificial intelligence, is shaping the current state of VTOL. These systems enhance operational efficiency, enabling greater reliability and safety. As these technologies improve, it looks like VTOL aircraft could become popular very quickly. This would make them a vital part of modern aviation. The significance of electric aircraft with Vertical Take-Off and Landing capabilities can take off and land in urban areas without the need for runways, making air transportation more accessible and reducing congestion on traditional ground routes. It drastically cut travel times within cities by providing direct routes and avoiding ground traffic, which is especially beneficial for emergency services and cargo delivery. Electric propulsion systems, designed in many e-VTOL aircraft, reduce emissions and contribute to a cleaner urban environment. The development and deployment of VTOL aircraft can create new job opportunities in manufacturing, maintenance, and air traffic management, boosting local economies.

The study aims to facilitate the integration of e-VTOL technologies into urban air transportation systems by adapting to upcoming regulations, making urban air mobility a viable and sustainable option for the future. The study addresses gaps in current regulatory frameworks by providing a comprehensive review of the existing regulations and identifying specific areas where modifications are needed to support the safe and efficient operation of e-VTOL (electric Vertical Takeoff and Landing) aircraft in urban environments. By addressing these areas, the study it proposes tailored policies that focus on:

Safety and Airworthiness Standards, Noise Levels, Collaborative Efforts, and Public Acceptance

Section 2 provides a Method which, overviews of the regulatory framework for the air transportation system; introduces the development of e-VTOL flying machines and the integrated mobility ecosystem; describes the technological changes affecting regulatory landscape uncertainty; outlines the advancement and implementation of regulation policy for e-VTOL air vehicles at an acceptable level issued by FAA and EASA; deals with the issued regulations, filling a gap in the literature, adding a legal framework status applicable for e-VTOL aircraft and giving the basis for a future pathway, Section 3 contains Result and Discussion, the Section 4 is includes Conclusion.

1.1 Development of e-VTOL flying machines by integrated mobility ecosystem

At the onset of the 21st century, a paradigm change transpired as traditional helicopters progressively yielded to e-VTOL flying machines, with developments accelerating in the ensuing decades. e-VTOLs exhibit considerable variation in speed, altitude, flight range, and passenger capacity, primarily offering diminished noise, reduced operational expenses, and improved safety (Al-Rubaye et al., 2023). Currently, international corporations including as Wisk, Archer, and Joby Aviation in the United States, Lilium, Airbus City, and Volocopter in Europe, along with EHang in China, are spearheading a new era in urban air mobility initiatives (Figure 1).

In the pursuit of sustainable and efficient transportation options, e-VTOLs are leading the charge in Urban Air Mobility (UAM). The rapid development of eVTOLs, designed to revolutionize air transportation as air taxis, leisure and emergency response vehicles, while improving freight transport capacity, is driven by advancements in battery technology, electric motors, and autopilot systems (Yan et al., 2023).

Fig. 1. e-VTOL air vehicle types

A crucial indicator of the e-VTOL business is the investment in diverse aircraft prototypes, particularly over the past five years. The terminology of UAM and on-demand mobility was presented during the inaugural meeting held in 2016 arranged by the Uber company, which redefined and envisioned urban air transportation network concept (Holden and Goel, 2016). The NASA concept "UAM maturity levels" outlines the progression of Urban Air Mobility through six phases, in which each step is dedicated to solving specific challenges concerning aerospace integration, social acceptance, and air vehicle technology development. These concepts outline a framework for the dynamic development of Urban Air Mobility (UAM) in the biggest metropolises (Goodrich and Theodore, 2021). Meanwhile, developers of urban air transportation networks such as Uber, Blade, and Airbus, being beginners-pioneers in airborne ride-sharing in charter services, demonstrated utilizing modern e-VTOL technologies and innovative business models in Sao Paulo and New York (Haynes and Alerigi, 2016; Uber, 2019) megapolises.

Many groups and companies are working on e-VTOL airplanes, a relatively new concept in the field of air mobility vehicle design. Compared to regular planes and helicopters, the new design architecture of these air vehicles is more efficient and faster, while ensuring flight safety. They utilize advanced materials, autonomous technology, and are equipped with batteries and electric propulsion systems, providing a new degree of urban mobility and allowing to change the way people travel in the future. Particularly for short- to medium-distance transit within future urban mobility, the air vehicles will be the best solution to provide efficient and fast movements. In terms of vehicle types, the most common ones are following (Partheepan et al., 2023)

Electric multicopters - Are small unmanned aerial vehicles (UAVs) with several propeller blades that run on electricity. The ability to take off and land vertically is an advantage and suitable to use in restricted spaces. Their typical range is about 50 km, and payload is accounted to take on board nearly 100 kg of cargo. Hybrid Tiltrotors - Air vehicles can go horizontal and vertical with the use of a mix of fixed wings and tiltable rotors. They are capable of carrying larger payloads of up to 1000 kg and can travel longer distances consisting of about 400 km (Dinc, 2020).

Electric fixed-wing e-VTOLs have the capability to get their lift from electric motors rather than propellers. With a range of about 100 kilometers, they require a runway for take-off and landing. They can handle loads as heavy as 500 kg. Unlike electric multicopters, hydrogen fuel-cell multicopters don't rely on batteries for propulsion but instead use hydrogen fuel cells. They are capable of carrying weights as heavy as 150 kg and have a range of up to 200 km. Gasoline-powered fixed-wing e-VTOLs are prototypes of the electric fixed-wing type; however, the power source is gasoline instead of electricity. The payloads are close to one ton and reach greater ranges of 500 km. The most common different aircraft type classifications of e-VTOL aircraft from the AAM/UAM family are wingless/multicopter, lift and cruise, and vectored thrust with particular advantages and disadvantages (EASA, 2021), (Figure 2).

Vectored thrust is able to gain the highest speed, enhanced maneuverability, improved performance, and reduced runway requirements; however, it has an increased weight, complexity, high maintenance cost, and limited range (Afridi et al., 2023).

Lift+Cruise air vehicles are developed to separate the functions of vertical lift and forward cruise. The key features are simplified design, which can reduce the complexity of transitioning between vertical and horizontal flight, and operational flexibility, the ability to operate propulsion units independently or in combination, ensuring versatile performance during lift, hover, and forward cruise. Increased weight and complexity, higher energy consumption, as well as limited range and speed, could potentially impact overall efficiency, which is a critical factor for electric vehicles (Memon,2023).

Wingless multicopters, referred to as multirotor air vehicles, are simple in control, able to perform complex aerial manoeuvres, can hover in place, and fly in any direction, and vice versa having shorter flight duration, lowest payload, and speed limitation (EASA, 2023a; Quan et al., 2020).

Fig. 2. e-VTOL type classification (EASA, 2021)

Furthermore, it is crucial to take into account the entire ecosystem of e-VTOL aircraft fields to ensure UAM operation. This ecosystem includes services such as fleet operations and physical infrastructure, which includes passenger hubs, terminals, vertiports, take-offs, and landing pads. The management of digital infrastructure improves safety and efficiency by using a control center for air traffic management (ATM), air traffic control (ATC), and communication-navigation-surveillance (CNS). The 5G network also has navigation aids built in. MRO services ensure the airworthiness of e-VTOL vehicles by performing maintenance, repair, and overhaul (MRO) tasks on demand and at scheduled service intervals. The physical infrastructure also includes the necessity of performing maintenance in hangar facilities, (Roland Berger, 2020).

Frost and Sullivan indicates that because to robust governmental support and continuous pilot initiatives, the United Arab Emirates (UAE), New Zealand, and Singapore are anticipated to be early adopters of Urban Air Mobility (UAM) systems. Dubai is poised to become the first city worldwide to commercialize air taxis. To initiate these services within the next two years, businesses like as Volocopter and EHang, in partnership with the UAE’s Roads and Transport Authority (RTA), have conducted extensive trials. New Zealand's commitment to the future of mobility is apparent; since 2017, Kitty Hawk (Cora) has executed around 1000 test flights in the Canterbury region. Singapore is poised to benefit from a first mover advantage. Volocopter is collaborating with various government organizations to evaluate the viability of launching commercial air taxi services in the city-state. Brazil and Mexico are also poised to be early adopters, intending to utilize their proficiency in helicopter taxis. Simultaneously, the United States has served as the epicentre of Urban Air Mobility (UAM) development, with over 70% of market stakeholders located within its borders (Vijayakumar, 2019).

2. Method

2.1 Overview of the regulatory framework for air transportation system

A comprehensive framework of aviation regulations has been instituted to facilitate the orderly conduct of air travel, examining the principal elements of international aviation regulations and emphasizing the functions of significant entities such as the International Civil Aviation Organization (ICAO), the Federal Aviation Administration (FAA), the European Aviation Safety Agency, the International Air Transport Association (IATA), and National Civil Aviation Organizations (NCAO). International aviation regulations are laws and standards developed to regulate several facets of worldwide air transport. These standards guarantee the safety, security, and efficiency of international flights, covering a comprehensive array of operational, technical, and legal stipulations.

International entities such as the International Civil Aviation Organization (ICAO), founded under the Chicago Convention of 1944, principally formulate and implement these regulations. The International Civil Aviation Organization (ICAO) advocates for member governments to implement its Standards and Recommended Practices (SARPs) to enhance uniformity and consistency in global aviation safety and operations. International aviation regulations encompass various domains, including aircraft operations, airworthiness, airport infrastructure, pilot certification, air traffic management, and environmental safeguarding. International aviation regulations seek to mitigate risks, prevent accidents, and facilitate uninterrupted air transport across national borders. These regulations also encompass matters such as passenger rights, liability in the event of accidents or incidents, and the legal framework governing international air services agreements between nations. Airlines, airports, and aviation staff must comply with these requirements to uphold uniform safety and security standards.

The commencement and proposal process generally commences with the identification of areas for regulation or the revision of existing standards. This could be prompted by technological improvements, safety accidents, environmental concerns, or alterations in global air traffic patterns. Member nations, international entities like the International Civil Aviation Organization (ICAO), or industry stakeholders advocate for new legislation or modifications. The structure of International Aviation Regulations involves a network of organizations and bodies of aviation stakeholders that collaborate to set up and develop standards for safe and effective worldwide air transportation (AnAviationServices, 2024).

Different national interests and agendas make it difficult to harmonize international aviation legislation; therefore, nations, international organizations, and industry players must continue to work together to promote a unified regulatory framework. New developments in aviation technology, such as electric airplanes and unmanned aerial vehicles (e-VTOLs, drones), have posed regulatory issues, and the current situation requires the responsible authorities to modify current laws to take these advances into account while maintaining operational integrity and safety.

Table 1. The structure of international aviation regulation (Adopted from Anaero, 2024)

International Aviation Regulatory Organizations	Functions
ICAO	A specialized UN institution in charge of establishing rules and standards for international aviation. In order to guarantee uniformity and consistency in aviation standards across the globe, it creates Standards and Recommended standards (SARPs), which member governments are urged to implement.
IATA	Speaks for the interests of airlines around the world. It creates operational guidelines, best practices, and industry standards to support the ICAO's regulatory needs.
Regional Intergovernmental CA Organizations	Handles regional aviation concerns and customizes aviation legislation to certain geographic areas and regional organizations. The Civil Aviation Organization of China (CAAC) in Asia and the European Union Aviation Safety Agency (EASA) in Europe are two entities aligning with the international standards established by ICAO while harmonizing rules within their respective regions.
Worldwide Intergovernmental Organizations	International aviation regulations are influenced by a number of global intergovernmental bodies in addition to the ICAO. These organizations, which complement ICAO's operations and offer a more comprehensive international framework for aviation cooperation and governance, include entities such as the United Nations (UN) and its several specialized agencies.
National Aviation Authorities	Each country has its own National Aviation Authority (NAA), which is responsible for regulating civil aviation within its borders and enforcing national regulations while aligning with international standards set by ICAO and EASA.
Non-Governmental Organizations	Contribute to international aviation regulations by offering regulatory processes support, lobbying, and experience. These organizations, which take part in debates, do research, and make recommendations to improve regulatory frameworks, include advocacy groups, academic institutions, and industry associations.

The regulatory landscape concerning e-VTOL technology is rapidly evolving; regulatory bodies like the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) are drafting frameworks to ensure safe operation and integration into existing airspace by adapting to the needs presented by these novel aircraft. Thus, changes to the regulatory framework for VTOL aircraft are essential in ensuring safety and efficiency. The new regulatory framework includes several key components, mainly consisting of airworthiness certification as a foundational aspect. In this context, the FAA and EASA are actively continuing to develop standards that specifically address the intricacies of VTOL operations. These standards encompass performance metrics, design criteria, and operational limits. In addition to airworthiness, pilot certification, and training requirements, they are also evolving. The introduction of electric and hybrid-electric VTOL aircraft necessitates new training protocols for pilots.

2.2 Technological change and regulatory landscape uncertainty

Regulatory challenges characterized by increased technological convergence associated with e-VTOL operation require the rapid development and fit-for-purpose regulatory frameworks. In this context, recent published research articles examine a number of regulatory challenges associated with unmanned developments (Du and Heldeweg, 2018).

Advances in engineering, manufacturing, and innovative technological change are accelerating the pace of development, resulting in a fundamental level of regulatory uncertainty. These developments include sophisticated simulation models. Novel software tools and Information and Communication Technologies (ICT) such as artificial intelligence, wireless 5G communication, and the miniaturization of electronics create opportunities for e-VTOLs to expand into the civil aviation sector with new use cases. A concomitant challenge of rapid innovation is regulatory uncertainty; moreover, it may result in expanding the uncertainty level and render regulatory action even more challenging (Du and Heldeweg, 2018).

The current regulatory frameworks primarily concentrate on preventive measures, which aim to reduce safety risks by adhering to established procedures and manuals. Nevertheless, advancements in battery technologies, electric motors, and the incorporation of cameras, sensors, and navigation systems in new aerial vehicles introduce supplementary hazards and challenges, requiring specialized regulatory frameworks (Finn and Donovan, 2016; Pagallo and Bassi, 2020).

Many national authorities are uncertain if current legislative frameworks facilitate the civil aviation sector's utilization of advanced AI-enabled drones in the future. Civil aviation authorities (CAA) serve as the primary regulatory and administrative entities engaged in the regulatory process under the existing framework. The existing breadth of the CAA's mandate constrains their capacity to handle pertinent issues. However, other CAAs suggest that the solution may lie not in broadening their scope, but in enhancing collaboration among pertinent producers, governmental bodies, and regulators to foster a conducive atmosphere for the swift advancement of the UAM industry. Numerous current legal systems may lack the capacity to address the difficulties posed by commercial e-VTOLs (World Economic Forum, 2019). Furthermore, there are potentially overlapping regulatory responsibilities between national regulations and local authority rules in the case of urban air mobility upon applying e-VTOL operations.

Despite the FAA and EASA having issued numerous regulatory amendments and annexes to existing regulatory acts, there are still challenges that need to be solved to provide success in integration into air transport networking. These rules cover the licensing of maintenance personnel and pilots, air vehicles, vertiports, air traffic management systems, and pertinent infrastructure that is under the regulations of aviation authorities. The requirements for each of these elements vary based on factors such as aircraft mass and performance, flight altitude, use cases, various licensing procedure levels, and the incorporation of regulatory methodologies into the legal systems (Jones, 2017). Furthermore, the technological standards for motor vehicles and conventional aircraft are distinct with broad and diversiform characteristics. According to Yan et al. (2023), Chinese transport authorities have defined 117 mandatory national standards for motor vehicles, while traditional commercial aircraft are subject to 18 only; in addition, there are 622 industrial, and 178 technical, standards, as well as 49 specialized criteria exclusions established for aviation.

Reconciling the standards is a serious challenge due to their different objectives and the technological setting achieved since their inception. The proliferated use of flying cars presents potential criminal issues, including hijacking. A perpetrator who seizes control of an aerial vehicle may face repercussions for both aviation and automotive hijacking, potentially leading to legal conflicts. Close relations with current policy support and legal interpretations are insufficient power to resolve these challenges. It is imperative to expedite the amendment and enactment of legislation pertaining to small flying machines and to integrate explicit legal annexes within applicable regulations and laws. This strategy will address the legislative discrepancies and disputes in their implementation. Furthermore, implementing a specialized compliance plan for flying cars throughout the airworthiness certification process can reduce risks and promote further growth. This strategy, a specialist compliance management system, will aid firms in traversing intricate regulatory frameworks, guaranteeing that flying automobiles are both secure and compliant (Yan et al., 2023).

2.3 Advancement and implementation of regulation policy for e-VTOL air vehicles at an acceptable level

The rapid progress in technology and the increasing global need for sustainable transportation have resulted in significant growth in e-VTOLs; however, regulatory and other obstacles must be addressed before these aircraft can be deployed in large-scale commercial operations. Regulations will and should embrace a comparably risk-averse strategy, how this may be addressed and ascertained, and what ramifications it may have for the sector's development (ITF, 2021). The Department of Transport (DOT), FAA, EASA, and Civil Aviation Authorities (CAAs) in various jurisdictions must persist in advancing and refining the essential aviation regulatory processes required for the commercialization of e-VTOL, specifically in design, production, and operating certification. Both regulators and companies will encounter new hurdles during this process, especially with autonomous e-VTOLs imminent, and decisions regarding aircraft design certification will profoundly influence the regulatory issues related to operations. Moving forward, alongside the aviation-specific regulatory frameworks for e-VTOLs, infrastructure, technological advancements, standards development, investment, and the establishment of comprehensive regulatory frameworks will be essential for the commercialization of e-VTOLs and the advancement of advanced air mobility. The regulations produced by the FAA and EASA provide an overview of the existing regulatory framework for UAM, emphasizing notable global advancements. These achievements signify a robust global initiative to create a unified regulatory framework for UAM.

The FAA and EASA is developing draft policies and recommendations to modify existing aviation laws in response to this new technology. The initial stage is acquiring a type certificate for an e-VTOL, which entails getting airworthiness approval for the aircraft and its components in accordance with its type design (EASA, 2010; FAA, 2017). The FAA utilizes one of two established certification processes in 14 CFR for e-VTOL type certification. Part 21.17(a) pertains to the assignment of relevant airworthiness requirements where the aircraft closely resembles the attributes of a specific airplane or rotorcraft category, combined with unique criteria to accommodate any discrepancies. The FAA employs an alternative procedure, Part 21.17(b), for specific categories of aircraft, implementing airworthiness standards sourced from other regulations as necessary.

The FAA is now deliberating on the applicability of airworthiness standards for Normal Category Airplanes as outlined in 14 CFR, Part 21.17(a) or Part 23, or the procedures specified in Part 21.17(b), to e-VTOL type certification (FAA, 2022; 2024a). The FAA has revised the airworthiness criteria in Part 23 to incorporate a performance-based methodology. The specific provisions for e-VTOLs under Part 21.17(a) and (b) will exhibit increased flexibility, and the certification transfer across jurisdictions may be more straightforward than the special class process (FAA, 2018).

Numerous contemporary e-VTOL concepts diverge markedly from existing certification criteria, and forthcoming concepts are anticipated to necessitate more modifications to the certification process (e.g., automation). Examples encompass distinctive aircraft configurations, electric distributed propulsion, energy storage and distribution systems, high-voltage architecture, fly-by-wire flight control systems, sophisticated or automated systems, crashworthiness criteria, and noise regulations. The FAA addresses these supplementary certification factors individually or via Issue Paper 4, which offers comprehensive system descriptions and elucidates the roles of certain systems and their interconnections, thereby facilitating the development of requisite standards by the FAA (2014).

After obtaining a type certificate, e-VTOL manufacturers must acquire a production certificate, which requires evidence of their ability to construct the aircraft in compliance with the same criteria. Companies seeking to fly e-VTOLs commercially must acquire an Air Carrier Certificate from the FAA in accordance with 14 CFR Part 135, which imposes supplementary safety, maintenance, performance, and operational standards. To engage in commercial operations, e-VTOL operators must secure economic authority from the DOT and comply with relevant US ownership and control regulations (FAA, 2024b). The FAA's decisions regarding eVTOL certification will significantly influence the applicability of existing regulations to future matters like as operations, pilots, and infrastructure, or need the creation of new regulations, due to the varying requirements of different aircraft types.

The European Aviation Safety Agency (EASA) published the “Design Verification Guide for Special Category Drones” in 2021, considering specifically applications for Urban Air Mobility air vehicle design. This approach is crucial to extensive effort, in which the EASA has created a regulatory landscape including fundamental regulation, namely the Basic Regulation for the VTOL Special Condition (EASA, 2019). These laws pertain to critical elements, including the classification of unmanned aircraft, the certification of VTOL aircraft, and the design of vertiports. The UK oversees Advanced Air Mobility (AAM) in accordance with EASA requirements by implementing a case-by-case strategy and fostering collaboration among manufacturers through programs including regulatory sandboxes and innovation funding (Gesley et al., 2023). The EU Regulations 2019/947 and 2019/945 establish the framework for the secure operating of drones throughout European airspace (EU and EASA Member States). They adopt a risk-based methodology and hence do not differentiate between recreational and commercial activity. They focus on the drone's weight, specs, and intended operation.

EU Regulation 2019/947, effective since late 2020, delineates three operational categories based on risk level: "open," "specific," and "certified." The "certified" category presents the greatest safety risk. Consequently, certification and license are necessary for the drone operator, the aircraft, and the remote pilot(s). In April 2021, the EU implemented U-space as a component of its drone regulatory framework. The European Commission states that U-space "establishes and standardizes the conditions necessary for the safe operation of manned and unmanned aircraft, to avert collisions between drones and other aircraft, and to reduce the risks associated with drone traffic on the ground" (European Commission, 2021).

In light of the expanding volume and range of drone operations in Europe, the European Aviation Safety Agency (EASA) has recently issued recommendations for drone operators, manufacturers, and state authorities. This guidance outlines the approach for design verification of drones categorized as 'particular'. This strategy is described as "a balanced approach that will promote innovation and growth in this promising sector." In a 2021 study, EASA investigated the views, expectations, and concerns of EU residents around UAM. The research concludes that EU citizens demand proactive and preventative measures behalf of authoritative entities. EASA (2021) indicates that there are instances that fulfill individual or private requirements. A recent ITF report indicates that authorities can enhance acceptance by educating the public on essential matters such as accident and incident statistics, grievance reporting and resolution processes, drone flight, take-off, and landing protocols, as well as the benefits of drone operations (ITF, 2021).

These approaches, while alleviating hazards associated with safety, security, noise, and environmental effect, seek to render UAM a collective advantage for society by offering accessible, integrated, and supplementary mobility. The concept of general/public interest is a crucial criterion for acceptance; use cases that help the community, such as medical or emergency transport and those linking rural places, enjoy greater support than those intended for private users, according to the study.

3. Findings and Discussion

Working on existing aviation regulations, in most cases the FAA approach is to draft policy and guidance to adapt them to e-VTOL aircraft, considering equipped new technology. However, EASA continues periodically to issue new regulations, particularly applicable to VTOL air vehicles, considering comprehensive design specifications and performances of air vehicles. Nonetheless, the successful implementation of UAM necessitates not only technological advancements but also the legal framework and social considerations to guarantee effective and safe operations. With the development and holistic investigations to define the challenges and legal perspectives, the European Union Aviation Safety Agency have introduced several systematic improvements to the regulations during the period 2017-2024 for the effective deployment of UAM operations. Table 2 provides a summary of the existing regulatory framework established for the execution of e-VTOL operations, emphasizing notable advancements worldwide. These developments signify a robust global initiative to create a cohesive regulatory framework for the UAM project.

The relatively rapid deployment of e-VTOL air vehicles, ensuring UAM operations, in turn raises concerns about the early stages of regulation and legal frameworks (Straubinger et al., 2020; Babetto et al., 2022; Sells and Crossley, 2022). Actually, the legal aspect includes the regulatory framework (Bauranov and Rakas, 2021; Mitchell et al., 2022). Authorities such as EASA and FAA, which work to establish standards and rules for the safe operation of e-VTOL air vehicles, are currently not subject to any specific restriction (Schuh et al. 2022) for test flights, following the regulatory implementations. This understanding is fundamental for developing effective legal frameworks and regulations that address, e.g., safety, noise, and integration within the manned space associated with air vehicles (Bauranov & Rakas 2021, Sun et al. 2021). Consequently, several initiatives and regulatory frameworks have been established in recent years to facilitate the secure integration of innovative aerial vehicles into urban settings in accordance with existing and forthcoming rules (Keller et al., 2021). The regulatory measures from 2017 to 2024 highlight the explanation of each regulatory item, the creation process, and the advancements achieved. Table 2 delineates the current legislative framework, highlighting the numerous hurdles that e-VTOL operations must surmount for complete integration into the airspace.

Table 2. Regulatory documents issued by FAA and EU-EASA

Year, Country/Region	Document N	Regulation and Policy Description
2005/2016, USA	14 CFR §23/ 81 FR 96689	Airworthiness Standards: Certification of normal category airplanes
2007/2017, USA	ORDER 8110.4C/ CHG 6	Type Certification
2009, USA	14 CFR Part 21.17(a) and (b)/ 74 FR 53384	Designation of applicable airworthiness standards along with special conditions used for special classes of aircraft
2018, USA	14 CFR Part 23, Notice No. 23-18-01-NOA/83 FR 21850.	Accepted Means of Compliance; Airworthiness Standards: Normal Category Airplanes
2024, USA	Q3 2024 Small Airplane Issues List 09/27/2024	Small Airplane Issues List
2024, USA	14 CFR Part 135, FAA Notice 8900.687	Air Carrier and Operator Certification
2001/2024, USA	14 CFR 145/Docket No. FAA-1999-5836, 66 FR 41117	Part 145-Repair Stations
2024, USA	Advisory Circular: AC 21.17-4	FAA Statement on e-VTOL Aircraft Certification. Type Certification—Powered-lift
2017, EU (EASA)	2017/373	Commission Implementing Regulation (EU) Air Traffic Management/Air Navigation Services (ATM/ANS). AMC/GM to Regulation 2017/373
2018, EU (EASA)	Regulation (EU) 2018/1139/Document 32018R1139	Basic Regulation on common rules in the field of civil aviation

2018, EASA	Doc. No: SC-VTOL-01/Issue: 1	Special Condition Vertical Take-Off and Landing (VTOL) Aircraft
2019, EU (EASA)	Delegated Regulation (EU) 2019/945/ 32019R0945	UAS systems and on third-country operators of unmanned aircraft systems
2019, EU (EASA)	Regulation (EU) 2019/947/32019R0947	Rules and procedures for the operation of unmanned aircraft
2019, EASA	Doc. No: SC-VTOL-01/Issue: 2	Special Condition for VTOL and Means of Compliance
2019, EASA	Doc. No. SC Light-UAS Medium Risk: Issue 01	Special Condition for Light Unmanned Aircraft Systems - Medium Risk
2019, EU (EASA)	Regulation 2019/1383; 2021/1963, ED	Annex 1 (Part-M), Annex 2 (Part 145) Annex III (Part-66), Annex IV (Part-147) Consider
2020, EU (EASA)	Commission Regulation 2020/639	Amending to 2019/947. Standard scenarios for operations executed in or beyond the visual line of sight
2021, EASA	Guidelines, Issue 1 (2023, Issue 3)	Guidelines on the design verification of UAS operating in the specific category
2021, EU (EASA)	Commission Regulation 2021/664/665/666	Regulatory framework for the U-space
2022, EU/Switzerland	Decision No 1/2022 of 2022/2471, Select: 1 C/2022/8516	Joint European Union/Switzerland Air Transport Committee
2022, EU (EASA)	Doc: PTS-VPT-DSN	Technical Specifications and Design of VFR Vertiports for VTOL-Capable Aircraft
2023, EASA	ED Decision 2023/013/R, to AMC and GM	Amended Reg's. Annex V a, b, c, d Part-M; Part-145 to Part-ML
2023, EASA	ED Decision 2023/019/R, to AMC and GM	Part CAMO TO Part CAO
2024, EU-EC (EASA)	Commission Delegated Regulation (EU) 2024/1107/1108/ 1109/1110/1111	EU-EC adoptable and implemented regulatory package, giving go-ahead for VTOL operations

The relatively rapid deployment of e-VTOL air vehicles, ensuring UAM operations, in turn raises concerns about the early stages of regulation and legal frameworks (Straubinger et al., 2020; Babetto et al., 2022; Sells and Crossley, 2022). Actually, the legal aspect includes the regulatory framework (Bauranov and Rakas, 2021; Mitchell et al., 2022). Authorities such as EASA and FAA, which work to establish standards and rules for the safe operation of e-VTOL air vehicles, are currently not subject to any specific restriction (Schuh et al. 2022) for test flights, following the regulatory implementations. This understanding is fundamental for developing effective legal frameworks and regulations that address, e.g., safety, noise, and integration within the manned space associated with air vehicles (Bauranov & Rakas 2021, Sun et al. 2021). Consequently, several initiatives and regulatory frameworks have been established in recent years to facilitate the secure integration of innovative aerial vehicles into urban settings in accordance with existing and forthcoming rules (Keller et al., 2021). The regulatory measures from 2017 to 2024 highlight the explanation of each regulatory item, the creation process, and the advancements achieved. Table 2 delineates the current legislative framework, highlighting the numerous hurdles that e-VTOL operations must surmount for complete integration into the airspace.

In the context of managing MRO organizations for e-VTOL aircraft, the general rules and regulations rely on existing frameworks applicable to traditional aircraft. The initial version of the basic management infrastructure under Part-145 is still in place, serving to define maintenance strategies for unmanned air vehicles. Due to changes in EASA regulations and issued amendments, Part-M is divided into Part-CAMO for commercial aircraft and Combined Airworthiness Organization (CAO) Part-CAO for light aircraft types by the implementing e-VTOL aircraft. The removal of Subparts G and F from Part-M will take effect from March 2022 for Part-CAMO/CAO. However, several changes to the requirement, applicable to Part-145 approved organizations, will take effect from December 2024. Regulation 1321/2014 allows the connection between the ongoing airworthiness of Part-CAMO/CAO and MRO Part-145 through PART-ML activities. Part-147-trained maintenance staff and Part-66-approved licensed personnel can sign releases to service for specific aircraft types (EASA, 2022; 2023b).

In summary, any operation is impeded by the absence of regulations and protocols, service providers, transparent integration with general aviation, and stringent airworthiness standards. These obstacles necessarily undermine the implementation and societal acceptance of the UAM operational system utilizing electric aerial vehicles (Babetto et al., 2023). The paper delineates a regulatory framework that acts as a foundation for overseeing UAM design drivers, particularly those related to e-VTOL aircraft. The legal obstacles might be encapsulated as an inadequate framework of regulations and protocols, coupled with a deficiency of service providers for operations in urban settings, which are essential for ensuring a secure and efficient aerial transportation service. In addition, collaborations between aircraft manufacturers, industry stakeholders, and regulators are crucial for advancing the acceptance and implementation of these aircraft. Hence, there is a necessity to establish guidelines that reflect these specialized operational characteristics.

Advances in electric propulsion systems applied to VTOL technology have seen significant improvements, enhancing the efficiency and performance of these aircraft. The application of electric motors powered by high-capacity batteries significantly reduces reliance on traditional fossil fuels, thereby promoting sustainability in aviation. Innovations in battery technology, such as improved lithium-ion and solid-state batteries, have increased energy density and reduced charging times. These developments enable longer flight durations and a more efficient power-to-weight ratio, making electric VTOL aircraft more viable for commercial applications in urban environments (Çorbacı and Doğan, 2023). Hybrid systems combining electric and conventional propulsion methods provide flexibility in operations, which allowing aircraft to operate in regions with limited charging infrastructure while benefiting from lower emissions during flight. The roles of automation and artificial intelligence (AI) are pivotal to shaping future trends in VTOL technology. Through advanced algorithms and machine learning, these technologies enhance flight safety, operational efficiency, and overall passenger experience in vertical takeoff and landing aircraft. AI systems facilitate real-time data analysis, enabling VTOL vehicles to make informed decisions during flight. The integration of automation enhances operational scalability in urban air mobility, allowing multiple VTOL aircraft to navigate congested airspace seamlessly. This interconnected network ensures efficient routing, minimizing delays and maximizing the utilization of air traffic resources. The environmental impact of VTOL aircraft is a critical area of study, particularly as urban air mobility concepts gain traction. Advances in electric propulsion systems are paving the way for reductions in noise and emissions, addressing concerns traditionally associated with aviation technology. Noise reduction technologies, such as quieter rotor designs and sound insulation, are being implemented to minimize the acoustic footprint of VTOL operations. This capability is vital for maintaining harmony in urban environments where aircraft might operate close to residential areas. Implementing regulations to control noise pollution is significant for e-VTOL aircraft operated in urban areas. Taking into account the public's perception and the social challenges associated with e-VTOL operations is crucial in addressing safety concerns and promoting urban integration among the population, all in line with the UAM concept.

There are several countries which actively integrating e-VTOL aircraft into their urban air mobility plans that could enhance the practical relevance future UAM operations. Archer Aviation has announced plans to establish an e-VTOL network in Los Angeles. United Airlines has placed orders for over 400 e-VTOLs with Archer Aviation and Eve Air Mobility. This initiative aims to alleviate traffic congestion and provide a sustainable alternative to traditional transportation. Singapore, the city-state, has been actively exploring e-VTOL technology for urban air mobility. Companies like Volocopter have conducted successful test flights in Singapore, showcasing the potential of e-VTOL aircraft in reducing travel times and improving urban transportation. Germany's company Volocopter has developed the VoloCity e-VTOL aircraft designed for urban air mobility and has undergone extensive testing and certification processes. It aims to provide a quiet, efficient, and environmentally friendly mode of transportation within big cities. Urban Aeronautics Ltd. (now Metro Skyways), based in Israel, has developed the CityHawk e-VTOL aircraft. This aircraft is designed for urban operations and can carry up to four passengers. It features ducted fans for vertical lift and horizontal flight, making it suitable for urban environments.

These approaches highlight the diverse applications and potential benefits of e-VTOL aircraft in urban air mobility. They also underscore the importance of infrastructure, regulatory frameworks, and technological advancements in realizing the full potential of this innovative mode of transportation (Kolar et al., 2024; Karsbergen, 2025).

4. Conclusion

The comprehensive framework of UAM using AAM aircraft encompasses multiple facets, involving innovations in technology, design architecture, basic operational structure, social perception, and analysis of market segmentations. Since their design, e-VTOL air vehicles have significantly advanced in battery technologies, propulsion systems, and electric motor enhancement. Numerous studies analyze diverse aircraft and propulsion designs, focusing on the roles of batteries, power electronics, thermal management, and the assessment of urban airspace concepts, including safety operations (Kim et al., 2018; Brelje and Martins, 2019; Bauranov and Rakas, 2021; Kai et al., 2022). The FAA, NASA, and EASA have developed various Concepts of Operations (ConOps) for the future use of Urban Air Mobility (UAM), with a focus on designing low-altitude airspace, managing start-up e-VTOL fleet operators, and establishing legislative frameworks for stakeholders in the UAM business environment. In addition to the existing research, regulatory frameworks play a crucial role in securing a prosperous future for urban transportation by tackling various legal obstacles. Different groups working together to create a UAM regulatory framework makes it easier to make big steps forward in certification, maintaining airworthiness standards, and making sure that reliable safety procedures and effective business plans work well together. This study highlights the need for further scrutiny of issued regulations by involved stakeholders and their partners, who are offering strategic initiatives, to effectively shape the future direction and growth of UAM use cases. Nowadays, the incorporation of UAM into urban air transportation systems presents technological and social problems, regulatory hurdles, and interoperability with current transportation infrastructures.

The early stages of regulation and legal status concerning e-VTOL aircraft essentially encompass the regulatory framework that contributes to the establishment of standards and rules for safe operation. Currently, the existing adapted regulations do not impose any specific restrictions on test flights or maintenance activities that support the airworthiness of air vehicles, even after temporary regulatory implementations. This is a fundamental factor for developing effective legal frameworks and regulations that address, e.g., safety, noise, and integration within the manned space associated with air vehicles. In recent years, have been implemented numerous initiatives and regulatory frameworks to ensure the safe integration of novel types of aerial vehicles into the urban environment, adhering to current and future regulations. The presented regulatory steps examined the issued document from 2017 to 2024, highlighted the description of each regulatory item, the development process, and achieved progress. Taking into account the current legal structure, there are some obstacles that must be overcome upon e-VTOL operations to achieve complete integration with the airspace. Overall, the absence of regulations and protocols, service providers, transparent harmonization with general aviation, and strict airworthiness requirements impedes any operation. These challenges inevitably compromise the deployment and public acceptance of the UAM operation system involving electric aerial vehicles. The regulatory framework, as outlined in this study, serves as a foundation for managing the design drivers of UAMs, which are typified by e-VTOL aircraft. The legal challenges can be summarized as an incomplete set of rules and protocols, as well as a lack of service providers for operations in the urban environment, which are crucial for providing a safe and efficient aerial transportation service.

Predictions for the future consider in increased adoption of the battery technology and autonomous systems continue to improve, that can expect a significant increase in the adoption of e-VTOL aircraft for urban air mobility. On the other hands the infrastructure development including vertiports and charging stations will become a priority to support the growing fleet of e-VTOLs. International regulatory bodies will work towards harmonizing standards to facilitate the global deployment of e-VTOL aircraft for successful UAM operations.

Regulatory organizations should collaborate closely with industry stakeholders to develop regulations that address the unique challenges of e-VTOL technology. Streamlining the certification process for e-VTOL aircraft will ensure safety without stifling innovation. Regulations should be focused on prioritize safety and sustainability, ensuring that e-VTOL operations do not compromise public safety and environmental standards. Investment in Public Awareness and Education will be major benefits for safety measures associated with e-VTOL technology (EASA, 2023).

CRediT Author Statement

Tapdig Imanov: All dimensions of the research are conducted by Tapdig Imanov.

Nomenclature

AAM : Advance Air Mobility
ATC : Air Traffic Control
ATM : Air Traffic Management
CAA : Civil Aviation Authority
CAO : Combined Airworthiness Organization
CNS : Communication Navigation Surveillance
DOT : Department of Transportation
EASA : European Aviation Safety Agency
EC : European Commission

EU : European Union

e-VTOL : Electric Vertical Takeoff and Landing

FAA : Federal Aviation Administration

FCL : Flight Crew Licensing

IATA : International Aviation Transport Association

ICAO : International Civil Aviation Organisation

ICT : Information and Communication Technology

ITF : International Transport Forum

MP : Maintenance Program

MPD : Maintenance Planning Document

MRO : Maintenance Repair Overhaul

NASA : National Aeronautics and Space Administration

NCAO : National Civil Aviation Organization

SERA : Standardized European Rules of the Air

UAM : Urban Air Mobility

UAV : Unmanned Air Vehicle

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Research Article

The Development of MRO Shared Services in Vietnam: A Comparative Analysis with Southeast Asian Countries

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Abstract

The MRO shared services market has experienced significant growth in Southeast Asia. These services provide airline operators with enhanced opportunities to streamline spare part procurement, reduce maintenance costs for engines and components, and improve fleet availability. By understanding the MRO shared services framework in Southeast Asia—comprising repair workshops and maintenance centers at key regional hubs—synergies can be created to boost performance in a short time. The MRO purchasing process within these shared services generates notable cost savings and efficiency improvements for airlines. The market's growth is driven by factors such as rising air traffic, increasing fleet sizes, and the need for regular maintenance and repairs to ensure safe, efficient aircraft operations. Compared to other countries in the ASEAN region, Vietnam, in particular, holds significant potential to position itself as a leading MRO hub in Southeast Asia. Its advantages include lower labor costs, a strategic location, and growing domestic demand for MRO services due to fleet expansions by airlines such as Vietnam Airlines, VietJet Air, Vietravel, and Bamboo Airways. However, to unlock this potential, Vietnam must address its shortcomings in infrastructure, technology adoption, and skilled workforce availability. Looking ahead, key trends are expected to shape the MRO shared services market, including expansion of MRO facilities, investments in technology, strategic partnerships and acquisitions, a focus on sustainability, and training and skills development. To capitalize on these trends, five essential measures should be adopted: investing in skill development, embracing digitalization, strengthening customer relationships, exploring partnerships and collaborations, and implementing sustainable initiatives.

Keywords

MRO shared services
Regional MRO hub
Airlines efficiency

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1. Introduction

Shared services have been widely researched across multiple disciplines offering insights into how organizations can centralize and standardize processes to improve efficiency, reduce costs, and enhance service quality, including:

- *Definition and Purpose*: Shared services refer to the consolidation of business operations (such as IT, HR, or finance) into a single entity that serves multiple parts

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of an organization. The primary objectives are cost reduction, quality improvement, and capability enhancement through process standardization and resource sharing (Fielt et al., 2014).

- *Strategic Benefits*: Shared services create value by enabling economies of scale and scope. By centralizing processes, organizations can minimize duplication, streamline workflows, and allocate resources more effectively. Shared services also allow for better alignment of operations with strategic goals, fostering innovation and agility (Fielt et al., 2014).

- *Digital Transformation*: Technological advancements, including automation, cloud-based solutions, and data analytics, play a key role in enhancing the effectiveness of shared services. Digitalization enables real-time monitoring, predictive insights, and process optimization, further improving service delivery (Fielt et al., 2014).

- *Stakeholder Involvement*: Successful shared service implementation requires collaboration across stakeholders, such as business units, leadership, and employees. Stakeholders must align on objectives, processes, and performance metrics to ensure a seamless transition and adoption (Fielt et al., 2014).

Overall, shared services serve as a strategic mechanism to achieve operational and financial efficiency while supporting broader organizational goals (Fielt et al., 2014; Jayaraman & Liu, 2019; Richter & Brühl, 2017). Continued advancements in digitalization and organizational design will further shape the role of shared services in modern enterprises. Shared services are regarded as a key approach to enhancing organizational performance (Wagenaar, 2006). Ruggini (2006) highlights that shared services typically encompass areas such as joint procurement, police and emergency services, and records management. The potential benefits of shared services include promoting efficiency, generating value, achieving cost savings, and improving service delivery for internal customers within the parent organization (Bergeron, 2003). Additionally, shared services play a significant role in bridging the gap between regional and local development by fostering collaboration and enhancing local service delivery (Michael et al., 2012).

In addition, literature reviews about shared services in the Maintenance, Repair, and Overhaul (MRO) industry and airline sectors reveal key findings around collaboration models, outsourcing strategies, and operational efficiencies.

- *Shared Services Models and Collaboration*: Shared services in MRO focus on reducing costs and improving efficiency by aligning operations across multiple stakeholders—airlines, OEMs, and third-party providers. Goncalves and Kokkolaras (2018) proposed a collaboration model that emphasizes shared facilities and aligned interests among these stakeholders, fostering resource optimization and regional synergies.

- *Outsourcing Decisions and Business Models*: A significant body of literature highlights outsourcing strategies in MRO as a way to enhance cost-efficiency. Airlines typically outsource non-core activities like engine repair and overhaul while retaining critical operations like line maintenance. Outsourcing of maintenance services has accounted for approximately 65% of airlines' technical expenditures (Jackson et al., 2023). A decision model for outsourcing in the airline sector suggests that balancing cost, quality, and turnaround time is key to adopting shared services (Goncalves and Kokkolaras, 2018).

- *Regional Competitiveness and Shared Service Development*: Comparative studies in Northeast Asia (China, Japan, Korea) show that shared services benefit from strong workforce capabilities, geographic advantages, and technological developments. However, challenges such as high labor costs and workforce shortages necessitate strategic investments in shared service platforms to sustain competitiveness (Goncalves and Kokkolaras, 2018).

- *Efficiency and Technological Integration*: Shared services are increasingly leveraging technologies such as predictive maintenance, remote monitoring, and data analytics to optimize operations. These initiatives streamline maintenance processes, reduce downtime, and enhance collaboration among service providers (Goncalves and Kokkolaras, 2018).

In the MRO industry, the implementation of shared services ensures aircraft airworthiness, extends operational lifespans, and reduces repair downtime. MRO shared service activities cover aircraft maintenance, routine inspections, component replacements, repairs, and upgrades (Mofokeng et al., 2020). The Southeast Asian aircraft MRO market includes a diverse range of participants, such as MRO shared services providers, original equipment manufacturers (OEMs), and airlines, all working together to maintain and improve aircraft performance. The demand for MRO shared services in Southeast Asia is expected to grow in the coming years, driven by the aviation industry’s expansion and the increasing emphasis on safety and regulatory compliance. Overall, the integration of shared services in the MRO and airline industries focuses on cost management, operational efficiencies, safety and regulatory effectiveness, fostering partnerships among key stakeholders. Strategic collaboration, investment in skills, and adoption of advanced technologies are critical to the development of shared services in this sector.

Table 1. Southeast Asia Aircraft MRO Market Size and Key Players (2024 – 2029)

Southeast Asia MRO Market Size	Key Players
Market size (2024): USD 3.77 Billion	Singapore Technologies Engineering Ltd. (ST Engineering)
Market size (2029): USD 6.49 Billion	Air Aisa Group Berhad
CAGR (2024-2029): 11.47%	Garuda Indonesia
Market Concentration: Medium	Philippines Airlines, Inc.
	PT.GMF AeroAsia
	Vietjet Air
	Thai Airways International Public Company Limited
	Malaysia Airlines Berhad
	Indonesia AirAsia
	VAECO - Vietnam Airlines Corporation

Source: Mordor Intelligence, MarkwiderResearch

The expansion of MRO facilities in Vietnam and Southeast Asia is a key driver of industry growth, with numerous centers offering varying levels of service specialization. Vietnam currently hosts several MRO centers, including VAECO, which provides comprehensive maintenance services, while other emerging facilities are focusing on specific aircraft components and line maintenance. Across the region, countries such as Thailand, Indonesia, and Malaysia have also invested heavily in expanding their MRO capabilities, increasing service capacity to accommodate growing airline fleets. Singapore remains the leading MRO hub in Southeast Asia, boasting world-class facilities such as ST Engineering Aerospace. The country's strong regulatory framework, highly skilled workforce, and advanced technological integration make it a benchmark for other nations seeking to enhance their MRO capabilities. Industry trends are also shaping the future of MRO services, with digital transformation playing a pivotal role in optimizing maintenance efficiency. The adoption of predictive maintenance, artificial intelligence, and big data analytics is streamlining repair processes and minimizing aircraft downtime. Additionally, the increasing diversity of aircraft types in operation necessitates specialized maintenance practices, further driving innovation in the sector. The presence of prominent players in the MRO shared services market has intensified competition, prompting aviation companies to prioritize service quality, cost efficiency, innovation, and collaboration to maintain a competitive edge. Strategic partnerships and collaborations between MRO shared services providers, OEMs, and airline operators are becoming increasingly common. These alliances foster knowledge sharing, joint research and development, and the delivery of integrated MRO solutions.

The MRO shared services market in Southeast Asia is experiencing robust growth, driven by expanding airline fleets, increasing air travel, and rising regulatory requirements for maintenance. According to the data presented, the market size is expected to grow from USD 3.77 billion in 2024 to USD 6.49 billion in 2029, reflecting a CAGR of 11.47%. This significant growth is fueled by the demand for cost-efficient, reliable maintenance services and the need to optimize aircraft downtime for operational efficiency.

Key players such as Singapore Technologies Engineering Ltd. (ST Engineering), Air Asia Group Berhad, Garuda Indonesia, Philippines Airlines, and Vietnam Airlines Corporation are driving competition in the region. Among these, Singapore continues to dominate as the leading regional hub, owing to its advanced infrastructure, strong workforce capabilities, and strategic geographic positioning. Meanwhile, countries like Vietnam are emerging as competitive alternatives due to lower labor costs and increasing investments in the aviation sector. However, Vietnam still faces significant challenges, including a lack of advanced technological integration, infrastructure constraints, and a shortage of highly skilled technical personnel.

Several trends are shaping the future of MRO shared services in Southeast Asia. First, there is a substantial focus on facility expansion, with investments in new hangars, maintenance centers, and training institutions to meet growing demand. Second, the adoption of advanced technologies such as predictive maintenance, automation, data analytics, and remote monitoring is helping streamline workflows and reduce aircraft downtime. Additionally, strategic partnerships and collaborations among MRO providers, airlines, and OEMs (Original Equipment Manufacturers) are becoming increasingly common, fostering knowledge sharing, enhancing service quality, and enabling access to global markets.

2. Methodology and Data Analysis

We are conducting qualitative research through interviews as an effective method to gain insights into the MRO market in Vietnam. This method allows for a deep understanding of industry trends, challenges, and opportunities, as shared directly by key stakeholders. The research aims to examine the development of

Vietnam's MRO market, highlighting key challenges and assessing its competitive position compared to other Southeast Asian countries. To achieve this, interviews will be conducted with a range of stakeholders, including MRO service providers—both local and international—who operate within Vietnam; airline operators such as Vietnam Airlines, VietJet Air, and Bamboo Airways; OEMs (Original Equipment Manufacturers) that supply components and foster partnerships; and aviation experts and regulators, including policymakers and industry consultants overseeing Vietnam's aviation sector.

Building on the collaboration model proposed by Cassio Dias Goncalves and Michael Kokkolaras (2018), as illustrated in Figure 1 below, we recommend that OEMs, MRO providers, and airline operators align their business objectives to create a collaborative ecosystem. This can be achieved by sharing MRO services and maintenance centers across the region, fostering greater synergy and operational efficiency.

Figure 1 presents a value and data flow model within the collaborative ecosystem of Original Equipment Manufacturers (OEMs), MRO providers, and airline operators in the Southeast Asian region. This model illustrates how resource sharing, data integration, and aligned business objectives can create synergies that drive operational efficiency, cost savings, and improved maintenance outcomes.

The value flow in this collaboration highlights the importance of mutual resource sharing among the three key stakeholders. OEMs provide critical resources such as spare parts, tooling, and technical data to MRO providers, enabling efficient and timely aircraft maintenance. Access to OEM data, particularly product specifications, repair manuals, and engineering updates, is vital for MRO providers to ensure the quality and accuracy of their maintenance activities. By leveraging these resources, MROs can optimize maintenance workflows, reduce turnaround time, and enhance operational reliability for airline operators.

The data flow aspect of the model emphasizes the exchange of real-time information across stakeholders. For instance, OEMs, such as commercial engine manufacturers, provide technical support and predictive maintenance insights based on advanced data analytics and remote monitoring solutions. This data flow allows MRO providers to anticipate maintenance needs, plan schedules proactively, and minimize unexpected downtime. Simultaneously, MRO providers feed operational data back to OEMs, enabling continuous improvement of product design and maintenance processes. Airline operators also contribute to the ecosystem by providing performance feedback and operational data, which helps both OEMs and MROs refine their services and align their strategies with the airlines' operational priorities.

This collaborative model fosters a win-win scenario for all stakeholders. For MRO providers, partnerships with OEMs and airline operators enable access to cutting-edge technologies, shared resources, and global expertise, enhancing their service quality and competitiveness. For OEMs, collaborating with MRO providers and airlines ensures stronger aftermarket support and long-term customer relationships. Airline operators benefit from improved fleet availability, reduced engineering and maintenance costs, and enhanced operational efficiency.

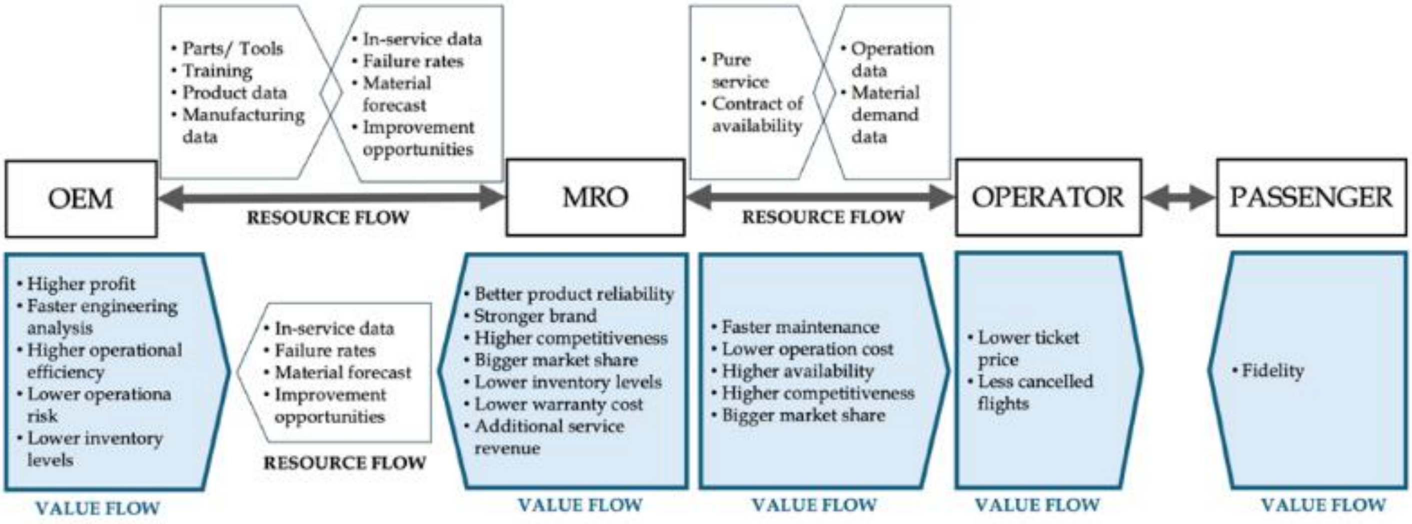

Fig.1. Proposed Value and Data Flow in OEM and MRO Collaboration

(Cassio Dias Goncalves and Michael Kokkolaras, 2018).

In the context of Southeast Asia, this model is particularly relevant as the region witnesses rapid fleet expansion and increasing demand for MRO services. By embracing collaboration, countries like Vietnam can address existing challenges such as infrastructure limitations, supply chain disruptions, and skilled workforce shortages. The value and data flow model also emphasizes the role of advanced technologies, such as predictive analytics and remote monitoring, in driving efficiency and aligning maintenance activities with global industry standards.

In conclusion, Figure 1 underscores the significance of collaboration among OEMs, MRO providers, and airline operators in the Southeast Asian MRO industry. The integrated flow of value and data across stakeholders creates a robust ecosystem that promotes operational efficiency, cost optimization, and innovation. For emerging markets like Vietnam, adopting this collaborative approach will be essential to modernizing MRO processes, strengthening regional competitiveness, and meeting the evolving demands of the aviation sector.

In addition, this research also examines interviews with OEM and MRO professionals from Southeast Asian countries, focusing on regional, categorical, and benefit-based factors where companies can mutually exchange critical resources. As illustrated in Figure 1 and supported by Casio and Michale (2018), essential resources for MRO activities include spare parts, tooling, equipment, and training. OEMs can collaborate with maintenance providers to gain access to product data, share spare parts and equipment, or provide technical training. By understanding the mutual benefits of collaborations among OEMs, MRO providers, and airline operators, we have developed a model based on the analysis of regional dynamics, resource categories, and associated benefits. This model identifies MRO shared services market trends and outlines key measures for MRO companies to effectively adapt to these emerging trends.

- *MRO Shared Services Regional Analysis*

The Southeast Asian region hosts several prominent MRO centers that provide a range of maintenance services, infrastructure, and technological advancements. In Vietnam, Vietnam Airlines Engineering Company (VAECO) is the leading MRO provider, offering line and base maintenance services, aircraft modification, and engine repair. VAECO operates multiple hangars and service facilities across major airports, including Noi Bai International Airport (Hanoi) and Tan Son Nhat International Airport (Ho Chi Minh City). The company is working toward international certification recognition to expand its global service network.

In Singapore, ST Engineering Aerospace is a dominant player with world-class MRO facilities specializing in airframe, component, and engine maintenance. The company is known for its investment in digital MRO solutions, predictive maintenance technologies, and automation to enhance service efficiency. Singapore's strategic location and advanced aviation infrastructure make it a preferred hub for airline maintenance.

Thailand is home to Thai Airways Technical Department, which provides comprehensive maintenance services, including aircraft heavy maintenance. Additionally, Bangkok Airways Maintenance Centre serves regional airlines with high-quality aircraft servicing capabilities. Thailand’s MRO facilities are expanding, with government initiatives supporting infrastructure development and skilled workforce training.

Indonesia's GMF AeroAsia, affiliated with Garuda Indonesia, is another significant MRO provider, focusing on full-service maintenance for aircraft fleets, component repair, and aircraft painting. The facility’s extensive capabilities and global partnerships contribute to its competitiveness in the region.

Malaysia’s Sepang Aircraft Engineering (SAE), a subsidiary of Airbus, specializes in aircraft heavy maintenance, structural repairs, and component servicing. The facility plays a key role in Airbus aircraft support in the region, reinforcing Malaysia’s MRO industry.

These MRO centers represent critical infrastructure supporting the growing aviation market in Southeast Asia. Their services range from routine line maintenance to complex structural repairs, engine overhauls, and advanced digital diagnostics. Strengthening Vietnam’s MRO infrastructure and aligning its capabilities with regional leaders through investment and technological innovation will be essential for competing in the evolving market.

- *MRO Shared Services Categories Analysis*

By examining specific shared services categories, we identify key factors across airframe maintenance services, engine overhaul services, component repair services, line maintenance services, and modification and upgrade services. These categories encompass activities such as inspecting, repairing, and maintaining aircraft structures, including the fuselage, wings, landing gear, and control surfaces; disassembling and reassembling aircraft engines; refurbishing critical components like avionics, landing gear, hydraulic systems, and electrical systems; and installing new equipment, systems, or features to enhance aircraft performance, safety, and efficiency.

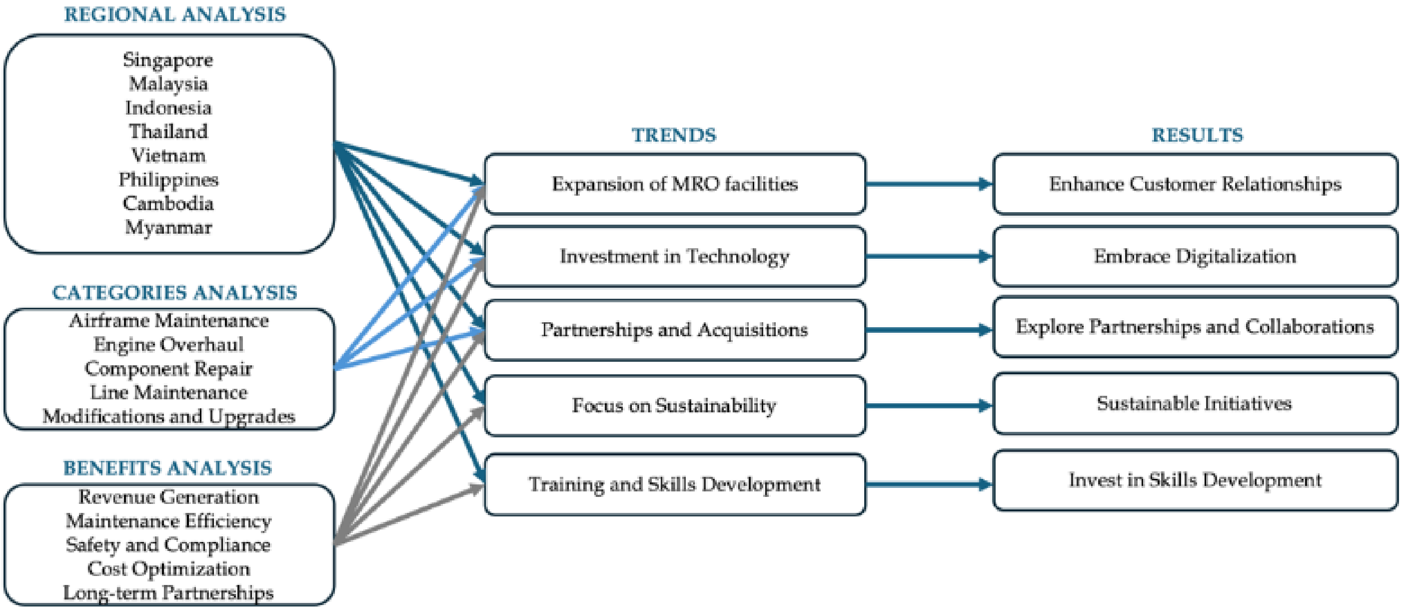

Fig.2. Southeast Asia Aircraft MRO Trending Results Developed by Authors.

- *MRO Shared Services Benefits Analysis*

MRO shared services provide significant mutual benefits, including revenue generation, maintenance efficiency, safety and compliance, cost optimization, and the establishment of long-term partnerships. By offering specialized expertise and services to airlines and OEMs, MRO providers generate substantial revenues, contributing to sustainable business growth. Efficient maintenance practices reduce aircraft downtime, enhance reliability, and minimize operational disruptions while ensuring compliance with regulatory standards and safety requirements in the aviation industry. Additionally, MRO shared services enable airlines and OEMs to optimize costs by leveraging the expertise and resources of specialized providers, fostering strong, collaborative relationships between MRO service providers, airlines, and OEMs.

The MRO industry in Southeast Asia has experienced steady growth, driven by an increasing fleet size across the region. Vietnam, Thailand, and Indonesia have witnessed significant expansions, with Vietnam's fleet size growing by approximately 10% annually. Meanwhile, Thailand and Indonesia have reported fleet growth rates of around 8% and 9%, respectively. A substantial portion of maintenance work continues to be outsourced, with nearly 60% of MRO services for Southeast Asian airlines performed outside their home countries, primarily in Singapore and Malaysia. This outsourcing trend highlights the need for enhanced local capabilities in Vietnam and other emerging MRO markets. Additionally, revenue from MRO services in the region is expected to surpass USD 6.5 billion by 2025, with Singapore maintaining a dominant market share, followed by Malaysia and Indonesia. These performance indicators underscore the importance of strategic investments in MRO infrastructure, workforce development, and technology adoption to ensure competitive positioning in the regional aviation industry.

To analyze the results presented in Figure 2, titled "Southeast Asia Aircraft MRO Trending Results," we can identify several key insights related to the region's MRO shared services market. The chart highlights a number of emerging trends and performance indicators that are critical to understanding the trajectory of the MRO industry in Southeast Asia.

The key trends depicted in the figure emphasize the growing demand for MRO services. As Southeast Asia experiences a rise in air traffic, expanding fleets, and stricter regulatory requirements, the need for reliable and efficient maintenance services has significantly increased. The figure illustrates how this growth is translating into higher demand for maintenance, repair, and overhaul services, both domestically and across the region.

The figure also highlights the integration of advanced technologies in the MRO sector, such as predictive maintenance, data analytics, automation, and remote monitoring. These technologies are revolutionizing MRO operations by streamlining workflows, reducing aircraft downtime, and improving overall operational efficiency. By leveraging real-time data and predictive insights, MRO providers can anticipate maintenance needs, optimize scheduling, and minimize operational disruptions, which ultimately leads to significant cost savings for airlines and improved fleet availability.

Another critical aspect addressed in Figure 2 is the emphasis on collaborations between key stakeholders in the MRO ecosystem. The figure demonstrates how OEMs, MRO providers, and airline operators are increasingly forming strategic partnerships to enhance the quality and efficiency of maintenance services. Through resource-sharing and data integration, these partnerships allow stakeholders to optimize their operations, reduce costs, and improve service delivery. This collaborative approach is vital for addressing challenges such as limited resources, skill shortages, and supply chain disruptions, especially as the region's fleets expand and require more frequent and specialized maintenance, particularly for aging aircraft.

In addition, Figure 2 highlights performance indicators such as revenue generation, maintenance efficiency, and workforce development. As the demand for MRO services rises, providers are generating more revenue through specialized services and cost-saving initiatives. However, these gains must be coupled with investments in skilled labor, as the industry faces a significant shortage of qualified technicians. Training programs, often in collaboration with educational institutions, are essential to ensure a steady pipeline of skilled professionals capable of supporting the industry's growth.

Lastly, the figure may point to the regional challenges and the strategic measures needed to overcome them. Issues like supply chain disruptions, technological adoption barriers, and the lack of advanced MRO facilities are likely depicted. To mitigate these challenges, countries like Vietnam must invest in expanding infrastructure, embracing digitalization, and forming stronger global partnerships. Additionally, a focus on sustainability is becoming increasingly important, with MRO providers adopting eco-friendly practices such as refurbishing components instead of replacing them, reducing carbon emissions, and investing in technologies that promote environmental responsibility.

In conclusion, Figure 2 provides a comprehensive overview of the key trends shaping the Southeast Asian MRO market. The analysis reveals a growing demand for MRO services driven by fleet expansion and increasing air traffic, alongside the adoption of advanced technologies to enhance operational efficiency. Strategic collaborations between OEMs, MRO providers, and airlines are critical to optimizing resources and improving service quality. By addressing challenges related to workforce development, infrastructure, and technology, Southeast Asian countries, particularly Vietnam, can strengthen their position in the global MRO market and drive sustainable growth.

3. Results and Discussion

Qualitative interviews provided valuable in-depth insights into Vietnam's MRO market, revealing key areas for development. The findings highlight the urgent need for infrastructure improvements, increased investments in advanced technology, and workforce training to address skill gaps. Additionally, fostering strategic collaborations with global players is critical for knowledge sharing and market expansion. These insights position Vietnam to capitalize on its cost advantages and strategic geographic location, enabling it to emerge as a competitive MRO hub within Southeast Asia.

The MRO industry in Vietnam faces several key challenges, with certification being one of the most significant obstacles. While Vietnam is home to large MRO organizations such as VAECO (Vietnam Airlines Engineering Company) for line maintenance and workshops, as well as smaller companies like Vietjet, Bamboo Airways, and Vietstar, the certifications required for international operations are still an issue. Within Vietnam, domestic operations are manageable, but the certifications issued by Vietnamese authorities are not yet recognized internationally by key aviation regulatory organizations such as FAA or EASA. This creates limitations, especially when it comes to offering MRO services for international airlines, preventing Vietnam from fully capitalizing on the global MRO market.

In terms of scale and capability, VAECO is competitive with MRO providers in the Philippines and Indonesia, countries that also have well-established MRO infrastructure. However, Thailand stands out in the region for its focus on workshops and component maintenance, which differentiates its MRO offerings from those in Vietnam. While Vietnam has some strengths in terms of cost advantages and a growing domestic market, it faces stiff competition in terms of specialized MRO services offered by its regional neighbors.

Regarding service sharing, VAECO predominantly provides line maintenance services for Vietnam Airlines (VNA), as well as some basic services for other customers (eg. Some domestic or foreign airlines). These services, however, are often restricted by the level of certification that is internationally recognized and legally required. While VAECO can perform maintenance services, including both line maintenance and heavy maintenance, for many airlines, especially domestic operators, it cannot fully leverage its capabilities, such as offering more advanced or specialized services, due to, for example, limitations in Vietnam's certification system which is not fully recognized by international aviation regulators (e.g., for specific types of aircraft and engines or components.)

Over the past decade, Vietnam's policy environment has significantly influenced the development of its Maintenance, Repair, and Overhaul (MRO) sector. Despite notable improvements, the regulatory framework remains restrictive, particularly regarding the approval and international recognition of MRO certifications. This constraint has limited Vietnam's ability to compete effectively with other Southeast Asian countries that have well-established MRO standards and globally recognized certification systems, such as those aligned with the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA). Without internationally accepted certifications, Vietnamese MRO providers face difficulties in attracting foreign airline clients and expanding their market reach beyond domestic operations. To enhance Vietnam's competitiveness, regulatory reforms should focus on aligning national certification standards with global aviation authorities, streamlining approval processes, and fostering strategic partnerships with international MRO stakeholders to build credibility and trust within the industry.

The supply chain disruptions have been another significant challenge for the MRO industry, particularly for companies like VAECO. The procurement of essential materials and parts has become increasingly difficult, resulting in delays and higher costs. These disruptions have made it harder for MRO providers to maintain efficient operations and meet the growing demand for maintenance services in the region.

To address these issues, Vietnam has started focusing on developing its human resources in the MRO sector. Companies like Vietjet have established ATP (Approved Training Providers) to train MRO staff. These training programs help workers obtain the necessary certifications required by the CAAV (Civil Aviation Authority of Vietnam). For employees without the required certification, additional training is necessary to meet the standard qualifications. Currently, only VAECO is authorized to conduct exams for Level B certifications, which makes it a key player in ensuring a skilled workforce for the MRO industry in Vietnam.

The market trend for MRO services in Vietnam has been improving, especially after the COVID-19 pandemic. The recovery of the aviation sector has led to an increase in demand for maintenance services across Southeast Asia, including Vietnam. As the fleet size of domestic airlines like Vietnam Airlines, VietJet, and others continues to grow, the demand for more efficient MRO services has followed suit. This presents an opportunity for Vietnam to strengthen its MRO capacity and increase its market share in the regional industry.

In terms of investment in infrastructure and technology, Vietnam has made progress, particularly with Vietnam Airlines pushing forward digitalization in the aviation sector. Projects such as the Maintenance Control System and the integration of data transfer systems between aircraft and operational maintenance control centers are helping to improve operational efficiency. These technological advancements enable better tracking and monitoring of aircraft maintenance, which is essential for reducing downtime and improving the overall effectiveness of MRO services.

Looking ahead, the prospects for Vietnam's MRO industry are highly promising. With a growing domestic market, investments in infrastructure and technology, and a rebound in air traffic, Vietnam is positioned to become a competitive player in the regional MRO industry. However, to fully capitalize on its potential, Vietnam needs to address the certification challenges, invest in workforce development, and continue expanding its MRO infrastructure. If these steps are taken, Vietnam could significantly enhance its position in the global MRO market. In summary, while Vietnam's MRO industry has considerable growth potential, it is currently hindered by certification issues, supply chain disruptions, and regulatory limitations. Nevertheless, with continued investments in training programs, technology adoption, and infrastructure development, the country is well-positioned to overcome these challenges and emerge as a key player in the Southeast Asian MRO sector.

- *Expansion of Fleet and Demand*

Vietnam's registered airlines, such as Vietnam Airlines and VietJet Air, have expanded their fleets significantly in recent years, resulting in a rising demand for MRO services. However, respondents pointed out that Vietnam's limited advanced MRO facilities often force airlines to outsource maintenance tasks to neighboring countries like Singapore and Malaysia. This trend underscores the need for local infrastructure upgrades to meet growing domestic demand and reduce reliance on foreign MRO providers.

- *Supply Chain Disruptions and Mitigation Strategies*

Supply chain disruptions, especially concerning engine components, have significantly impacted MRO operations in recent years. To mitigate these challenges, MROs are employing various strategies such as collaborating closely with Original Equipment Manufacturers (OEMs) to expedite material delivery, exploring alternative materials where possible, and strategically scheduling maintenance events to optimize aircraft utilization. While diversifying suppliers is recognized as a crucial risk-reduction measure, it remains challenging when dealing with major OEMs due to their dominant market positions. Additionally, the industry faces a critical shortage of skilled technicians, emphasizing the need for robust manpower management and comprehensive training programs. These multifaceted approaches aim to enhance resilience in the face of supply chain uncertainties while ensuring the availability of a competent workforce to meet the growing demands of the MRO sector.

- *Investment in Infrastructure*

Leading MRO providers, including VAECO (Vietnam Airlines Engineering Company), have made efforts to expand their maintenance capabilities. Despite these advancements, capacity limitations remain a significant challenge. Respondents emphasized the importance of further investments in infrastructure, including new maintenance hangars and technology upgrades, to strengthen Vietnam's MRO capabilities and better serve the expanding aviation sector.

- *Competitive Position*

Vietnam offers cost advantages, particularly lower labor costs, when compared to established MRO hubs like Singapore and Malaysia. However, respondents acknowledged that Vietnam lags behind in terms of scale, technological sophistication, and global reputation. Strategic partnerships with international players were identified as a crucial step to enhance service quality, build credibility, and compete effectively in the Southeast Asian MRO market.

- *Technology Adoption*

OEM representatives stressed the importance of integrating advanced technologies, such as predictive analytics, automation, and remote monitoring, into Vietnam’s MRO processes. These digital solutions can significantly reduce aircraft downtime, streamline maintenance workflows, and improve overall operational efficiency. Investing in such technologies will allow Vietnam to modernize its MRO sector and align with global industry standards.

- *Skilled Workforce*

A recurring concern among respondents was the shortage of highly skilled technical personnel in Vietnam's MRO sector. The MRO sector faces significant challenges in attracting young talent, with many potential recruits opting for alternative career paths. Despite the existence of training programs, there's a noticeable lack of resources and interest in MRO careers. The industry recognizes the critical importance of digital transformation to enhance efficiency and competitiveness, although implementation is often hindered by cost constraints. To address this challenge, respondents suggested fostering collaboration with vocational schools, universities, and international training programs. These alliances not only help in sharing resources and expertise but also play a crucial role in improving overall efficiency and reducing operational costs. This collaborative approach is seen as a key strategy in overcoming the sector's recruitment and technological hurdles while ensuring its long-term sustainability and growth, and build a robust pipeline of qualified MRO professionals, ensuring Vietnam’s workforce can meet the growing demands of the aviation industry.

- *Sustainability Initiatives*

Sustainability is emerging as a critical focus area for Vietnam's MRO industry. MROs are embracing innovative technologies to enhance efficiency and competitiveness in the aviation maintenance sector. Some interviewees highlighted the importance of eco-friendly practices, such as refurbishing and reusing aircraft components instead of replacing them. These initiatives not only reduce costs but also align Vietnam’s MRO industry with global environmental standards, positioning the country as a forward-thinking and responsible player in the market. Aircraft health monitoring systems and drone dent mapping are among the cutting-edge solutions being implemented. While the aviation industry has traditionally been slower to adopt new technologies compared to other sectors, recent years have seen a significant push towards modernization, particularly in the wake of COVID-19. The regulatory environment, especially in Vietnam, is increasingly focusing on sustainability issues such as reducing carbon emissions and improving waste management practices. However, the pace of adoption for sustainable innovations in Vietnam's MRO sector still lags behind more advanced markets like the European Union. As the industry evolves, MROs are exploring various technological and procedural improvements to streamline operations, reduce costs, and meet growing environmental concerns, all while maintaining the highest safety standards.

A notable trend is the growing emphasis on sustainability within the MRO sector. Companies are implementing eco-friendly initiatives, such as refurbishing and reusing aircraft components, to minimize costs and align with global environmental standards. This aligns with the broader industry goal of reducing carbon emissions and adopting greener practices. Furthermore, addressing the skills gap remains a critical focus, with efforts to collaborate with vocational schools, universities, and international training programs to build a skilled workforce capable of supporting the industry's long-term growth.

Vietnam, in particular, holds significant potential to position itself as a leading MRO hub in Southeast Asia. Its advantages include lower labor costs, a strategic location, and growing domestic demand for MRO services due to fleet expansions by airlines such as

Vietnam Airlines, VietJet Air, Vietravel, and Bamboo Airways. However, to unlock this potential, Vietnam must address its shortcomings in infrastructure, technology adoption, and skilled workforce availability. Investments in modernizing facilities, embracing digitalization, and fostering global partnerships will be essential for Vietnam to compete with established players like Singapore and Malaysia.

In short, Vietnam's growing MRO market presents significant trends and opportunities, driven by the rapid expansion of domestic airline fleets, including Vietnam Airlines, VietJet, and Bamboo Airways, which has increased demand for maintenance services and fleet modernization. Regional collaboration with neighboring Southeast Asian countries to establish shared MRO hubs offers cost reductions and economies of scale by serving regional carriers. The focus on digital MRO solutions, such as predictive maintenance, artificial intelligence, and blockchain for inventory management, is transforming operations by enhancing efficiency and reducing turnaround time. Government support through investments in infrastructure, airport development, and partnerships with international stakeholders further strengthens Vietnam's MRO capacity. Additionally, Vietnam's competitive advantages, such as lower labor costs and a growing pool of skilled technical professionals, position the country as a cost-effective alternative to established MRO hubs like Singapore and Malaysia, offering quality services at a reduced cost.

Through our research analysis, we have identified five key trends driving the growth of the MRO shared services market in Southeast Asia: (1) Expansion of MRO Facilities, (2) Investment in Technology, (3) Partnerships and Acquisitions, (4) Focus on Sustainability, and (5) Training and Skills Development. These trends are expected to significantly contribute to the future development of the MRO market.

MRO shared services providers are expanding their infrastructure by establishing new hangars, maintenance centers, and training institutions. Companies are also investing in advanced technologies, including data analytics, automation, robotics, and cloud-based solutions, to streamline maintenance processes, improve decision-making, and enhance operational efficiency and customer service. Strategic partnerships and acquisitions are increasingly prevalent, fostering collaboration between OEMs, MRO providers, and airline operators.

Another significant trend is the growing focus on sustainable practices to minimize environmental impact. This includes initiatives such as refurbishing aircraft components, optimizing fuel consumption, and investing in sustainable technologies. Finally, MRO providers are prioritizing training programs to develop a skilled workforce, enhance technical expertise, and ensure a steady pipeline of qualified professionals. This focus on workforce development addresses the potential shortage of skilled workers in the future, further strengthening the MRO industry.

The future of the MRO industry hinges on a delicate balance of efficiency and safety, as emphasized by the industry expert. To ensure long-term success and sustainability, MROs must prioritize innovation, forge strategic partnerships, and invest in robust training programs. The expert advises a pragmatic approach: focus on mastering basic maintenance tasks while gradually integrating new technologies and processes to enhance efficiency. This measured strategy allows MROs to maintain high safety standards while steadily improving their operations. The industry's growth and development will likely benefit from the sharing of knowledge and experience among seasoned professionals, fostering a collaborative environment that drives continuous improvement and adaptation to evolving challenges in the aviation maintenance sector.

In conclusion, the MRO shared services market in Southeast Asia is on a promising trajectory, driven by expanding fleets, technological advancements, and increasing regional collaboration. Vietnam, while facing challenges, is well-positioned to capitalize on its cost advantages and strategic location. To fully realize this opportunity, the country must focus on enhancing infrastructure, adopting advanced technologies, and developing a robust talent pipeline. These measures, combined with sustainability initiatives, will ensure Vietnam's emergence as a competitive and forward-thinking player in the regional MRO market.

4. Conclusions

Based on the identified trends, we propose five key strategies to effectively adapt: (1) Investing in Skills Development, (2) Embracing Digitalization, (3) Enhancing Customer Relationships, (4) Exploring Partnerships and Collaborations, and (5) Implementing Sustainable Initiatives.

First, to address the shortage of skilled personnel and ensure a competent workforce, MRO shared services providers should invest in training and skills development programs in collaboration with educational institutions and vocational training centers. Second, embracing digitalization and advanced technologies—such as data analytics, predictive maintenance, and remote monitoring—will optimize maintenance processes, enhance operational efficiency, reduce costs, and improve safety.

Fig.3. Strategic Adaptations developed by authors.

Third and fourth, strengthening relationships with airline operators and OEMs will enable MRO providers to expand their capabilities, access new markets, share resources, and create synergies that unlock further opportunities. Fifth, prioritizing sustainability initiatives will align MRO providers with industry trends and customer expectations. This includes adopting eco-friendly practices, reducing carbon emissions, and exploring innovative solutions to foster a cleaner and more sustainable MRO industry.

Despite promising opportunities, the MRO industry has faced significant challenges in the post-COVID era, as discussed in our recent interviews., including infrastructure limitations due to the constrained capacity of existing facilities and the need for expansion to meet rising demand. The country also faces intense global competition from well-established MRO markets such as Singapore and Thailand, which boast advanced infrastructure, technology, and global reputations. Supply chain disruptions, workforce shortages, and rising costs have created a complex operating environment. The sudden surge in demand for aircraft maintenance following the pandemic has led to a scarcity of maintenance slots and escalating expenses, compelling airlines to seek services beyond their usual geographical areas. Additionally, while Vietnam's workforce is improving, continued investment in technical skill development is necessary to meet international MRO standards.

To address these challenges, the industry is increasingly turning to shared services and partnerships between MROs and airlines, aiming to boost efficiency and manage costs. Additionally, the adoption of innovative technologies like drone dent mapping is playing a crucial role in enhancing maintenance processes and overall operational effectiveness in this new landscape. By addressing these challenges through regional partnerships, strategic collaborations, and a strong focus on digital transformation, Vietnam has the potential to emerge as a significant MRO hub within Southeast Asia.

In conclusion, the Southeast Asian Aircraft MRO market is driven by rising air passenger traffic, expanding fleet sizes, and the increasing need for regular maintenance and repairs. Despite challenges such as workforce shortages and rising operational costs, the MRO shared services market presents significant opportunities, including revenue generation, improved maintenance efficiency, enhanced safety and compliance, and the establishment of long-term partnerships. Strategic investments in digitalization, skills development, infrastructure, and sustainability will be essential for achieving success in this evolving market and contributing to the economic growth of the Southeast Asian region. To strengthen the study's rigor, a mixed-methods approach can be employed for further research, combining qualitative and quantitative data collection. Qualitative data can be gathered through in-depth interviews with key stakeholders, including MRO providers, airline operators, policymakers, and industry experts. This will provide valuable insights into regulatory challenges, market trends, and operational constraints. Quantitative data should include industry reports, statistical analyses of MRO market growth, and financial performance metrics of major regional MRO providers. By integrating both qualitative and quantitative methods, the study can offer a well-rounded assessment of Vietnam's MRO sector. Additionally, employing a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis would provide a strategic evaluation of Vietnam's position in the regional MRO market. Strengthening these aspects will contribute to a more comprehensive and compelling analysis of Vietnam's evolving role in the Southeast Asian MRO industry.

Nomenclature

ATP	: Approved Training Providers
CAAV	: Civil Aviation Authority of Vietnam
CAGR	: Compound Annual Growth Rates
EASA	: European Union Aviation Saferty Agency
FAA	: Federal Aviation Administration
MRO	: Maintenance, Repair, and Overhaul
OEMs	: Original Equipment Manufacturers
VAECO	: Vietnam Airlines Engineering Company

CRediT Author Statement

Tran Thi Thai Binh: Conceptualization, Methodology, Validation, Interview, Formal Analysis, Data Curation, Writing- Original Draft Preparation, Visualization, Supervision, Project Administration. **Nguyen The Hoang**: Resources, Interview, Reviewing and Editing, Visualization, Funding Acquisition.

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Research Article

Integrating Additive Manufacturing and Composite Manufacturing Techniques to Build a General-Purpose UAV

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Abstract

The development of unmanned aerial vehicles (UAVs) and their integration into our daily life have rapidly accelerated in recent years. Despite these advancements, the production of UAVs often requires specialized and costly equipment. However, with the rapid evolution of additive manufacturing (AM) technologies, it is now possible to design lightweight, optimized structures that can be manufactured easily and quickly. This approach enables faster design iterations, reduces the need for multiple parts and material usage during production, and significantly minimizes waste. A hybrid UAV combines the advantages of vertical take-off and landing (VTOL) capabilities with the efficient cruising performance of a fixed-wing aircraft. This study investigates the feasibility of using AM for the manufacturing of a 3.8-meter wingspan hybrid UAV. The system consists of two components: a hybrid aircraft and a parachute drone carried by the hybrid aircraft. Following the mechanical and aerodynamic design of the air vehicle, it was fabricated using a rapid prototyping approach that integrates AM and composite production techniques. This study demonstrates that even large-scale UAVs can be produced with AM-supported design and manufacturing. This method supports on-demand customization, reduces material waste, and promotes innovation and sustainability in UAV production. It is anticipated that this approach can make UAV production more accessible to the general public, potentially accelerating the development of UAV technology.

Keywords

Additive Manufacturing
Hybrid UAV
Parcel Delivery UAV
Vacuum Infusion Method

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1. Introduction

Unmanned aerial vehicles (UAVs) (also called drones) are autonomous or remote-controlled aerial vehicles ranging from small enough to fit in the palm of your hand (21 cm) to a wingspan of 42 meters. Although the word drone is used instead of UAV, it is preferred to refer to smaller, consumer-class models weighing 2 kg and below. UAV or Unmanned Aircraft System (UAS) is preferred for professional aircraft.

In recent years, along with the developments (Mohsan et al., 2023; Telli et al., 2023; Çetinsoy et al., 2012; Hissa and Mothé, 2018), we have witnessed their useful applications in the fields of defense (Chaturvedi et al.,

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2019), agriculture (Radoglou-Grammatikis et al., 2020; Srivastava et al., 2023), health (De Silvestri et al., 2023; Boutilier et al., 2017; Ackerman and Strickland, 2018), logistics (Li et al., 2022; Koetsier, 2021; DHL), transportation (Rajendran and Srinivas, 2020; Smirnov et al., 2023; Kellermann et al., 2020), and search and rescue (Lyu et al., 2023; Martinez-Alpiste et al., 2021). Although UAV technology has progressed, manufacturing requires specialized equipment and intricate procedures. The rise of rapid prototyping, driven by 3D printers (Shahrubudin et al., 2019), has made custom production of various items more accessible to everyone. As the 3D printing techniques emerged, using these technologies for UAV manufacturing was inevitable. The approach has the potential to reduce weight, manufacturing costs, and deployment time (Moon et al., 2014; Ferro et al., 2016).

For a mini drone, designing and printing a drone model with a 3D printer is common. Various studies share their findings (Esakki et al., 2019; Klippstein et al., 2018; Goh et al., 2017).

According to the literature, the first printed plane was the Southampton University Laser Sintered Aircraft (SULSA) in 2011 (Marks, 2011). Small drones and UAVs were manufactured using 3D printers (Banfield, 2013; McKinnon, 2016). British Royal Navy successfully launched a 3D-printed UAV for maritime patrol missions in 2016 (3D printing industry, 2016). (Aktas et al., 2016) presents the iterative design process of the TURAC, a VTOL UAV. It emphasizes a low-cost prototyping methodology. A master's thesis discusses the role of rapid prototyping in developing a novel amphibious UAV (Zlatan, 2021). There are various demonstrations and failures with printed propellers. (Biswas et al., 2018) reveals that the 3D-printed propeller experiences higher stress levels throughout its structure compared to the non-3D-printed propeller, making it more susceptible to breaking. On the other hand, (Alves et al., 2021) propose solutions to overcome failures and compare wind tunnel tests to numerical predictions for validation. Recent studies propose a quieter Toroidal Propeller designed with computational fluid dynamics (CFD), and manufactured with 3D printing techniques as an alternative (Jansen, 2024). A patent by (Sebastian and Strem, 2017), with (MIT, 2023) proposes a significant reduction of discernible noise.

Weight reduction is one of the critical goals of aerial system design. One can use internal lattice structures and numerical topology optimization to reduce the weight of UAVs. (Yap et al., 2023) argues that topology optimization combined with 3D printing offers a safe and reliable approach to micro-UAV design and prototyping. Isotropic materials exhibit the same physical properties (e.g., strength) in all directions. However, 3D printing procedures and some materials used can lead to anisotropy in many 3D printed objects. Therefore, it is necessary to validate the material's strength through destructive or non-destructive testing.

The wings and control surfaces of an aircraft are vital components that require a balance between strength and weight. This can make their manufacturing challenging and costly. Combining 3D printing and composite manufacturing offers a promising approach to making aircraft components more affordable and efficient. Wings and other control surfaces can be manufactured using the Vacuum Infusion Process (VIP), a technique that leverages vacuum pressure to impregnate resin into a laminate (Baker, 2004).

Table 1 compares standard versus additive manufacturing techniques across various factors.

This study explores the feasibility of manufacturing a 3.8-meter hybrid UAV with the fused deposition modeling (FDM) technique and the use of VIP. An FDM 3D printer was used to create the aircraft body, various parts, and molds for VIP. Wings and control surfaces were built via VIP. The study involves aircraft design, manufacturing techniques, and assembly procedures.

Table 1. The comparison of standard versus additive manufacturing techniques

Factor	Standard Manufacturing	Additive Manufacturing
Design Flexibility and changes	Limited (by the machines and operator skills)	High (complex, lightweight, and optimized designs possible)
Manufacturing Ease	Low (needs special machines, tools, skilled labor)	High (due to minimal setup and layer-by-layer manufacturing)
Manufacturing Cost	High (high machine investment, tooling, setup, and labor costs)	Low (for small batches)
Initial investment	High (equipment, tooling)	Medium
Structural Strength	High	Variable (depends on material selection)
Ease of part repairs	Low (usually requires manufacturing of replacement parts)	High (Rapid and cost-effective)
Environmental Impact	High (energy use and material waste)	Low (less waste)

This paper is organized as follows. In Section 2, aerodynamic and mechanical design to develop a UAV for a particular task has been explained. Manufacturing techniques, post-processing operations, and assembly of the aircraft are explained in detail in Section 3. Final remarks on cost and delivery time benefits were presented in Section 4. Conclusions and future work are given in Section 5.

2. Design of the Aircraft

UAV design and manufacturing process involves various steps as outlined in Figure 1. The process starts with *Concept & Design* phase where the main design will be created. Once the design is ready, the *prototype development* phase will follow, which usually involves building a small-scale version of the aircraft for concept, visual, or wind tunnel testing. Once the design proves to be acceptable the team can proceed to *Manufacturing & Assembly* phase. All the materials for manufacturing, propulsion, control, and electronical parts will be purchased. The wings, body, and control surfaces of the aircraft will be manufactured. Electronic cards may be designed. Quality of the manufactured parts should be checked before proceeding to the assembly step, where the frame, body, propulsion system, electronic parts such as sensors, and battery will be assembled. This step may also require software installation for controllers, telemetry systems, and ground station (if any). Once the aircraft is complete *Testing & Validation* phase will start. The team will perform functional testing of each subsystem, flight testing, as well as any other tests required by regulations. If there are any problems, the team may need to update, redesign, or re-manufacture certain parts to overcome the problem. If the testing phase is completed successfully and there is a market for the aircraft, the team may proceed to the Production & Deployment phase, in which the system will be redesigned and updated for mass production, following additional tests and quality control inspections, and delivery to clients for usage.

The design steps are outlined in Figure 1 *Concept & Design* phase, involves identifying requirements and defining specifications. Once this step is complete designer has a set of constraints to begin CAD modeling of the aircraft. Various simulation environments can guide the designed in the design process. Once the design proves to be feasible, the team will start building a prototype system.

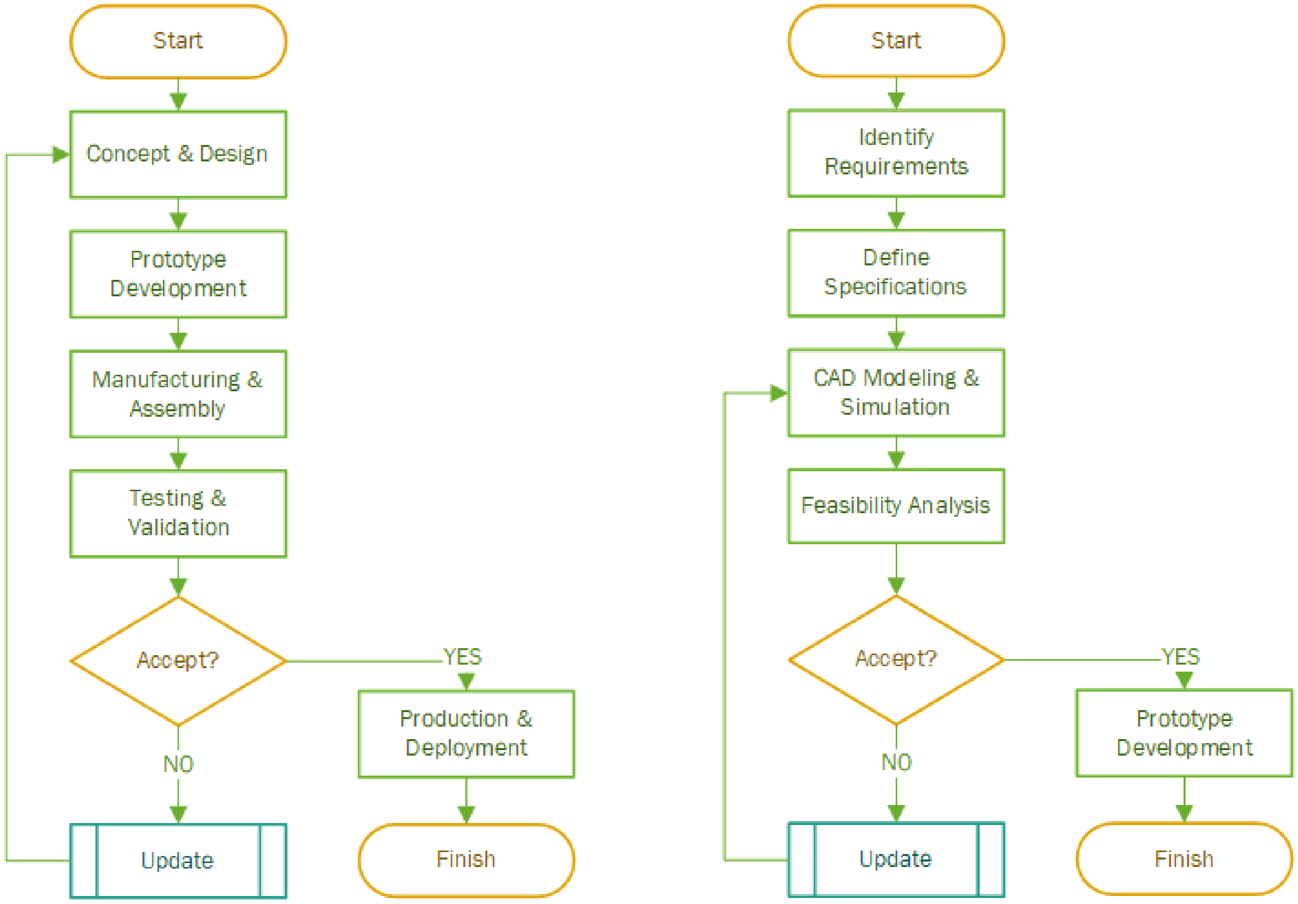

Fig. 1. UAV design and manufacturing flowchart (left). Concept and design flowchart (right)

The design of the aircraft involved detailed aerodynamic analysis and mechanical design. Various iterations were performed to achieve the final design. The starting goal is to design a UAV that can deliver books from the Faculty building to the main library (7.78 km). For flights involving low Reynolds number, we used XFLR5 software containing CFD to obtain an aerodynamic database for trim analysis and non-linear simulations. XFLR5 uses XFOIL (Drela and Young, 2013) to perform direct or indirect airfoil analysis.

For the aerodynamic analysis of the wing and tail, the XFLR5 program with the Vortex Lattice Method (VLM) and the Panel Method were used. Comparing takeoff speed and stall speed, or wings with different airfoils could be possible. Aerodynamic analysis of the body was performed with CFD in Simscale (SimScale, 2023).

Figure 2 presents the rendered aircraft. The final UAV specifications are given in Table 2.

The flight time in helicopter mode is estimated to be 10 minutes and the hybrid flight time is approximately 18 minutes. Considering the 21 m/s gliding speed, which was also chosen as the design criterion, the range was estimated to be approximately 16 km, regardless of the transceiver restriction. This range, when the coordinates between the faculty building and main library are calculated, which is 7.78 km, is sufficient considering that the drone takes off from these settlements.

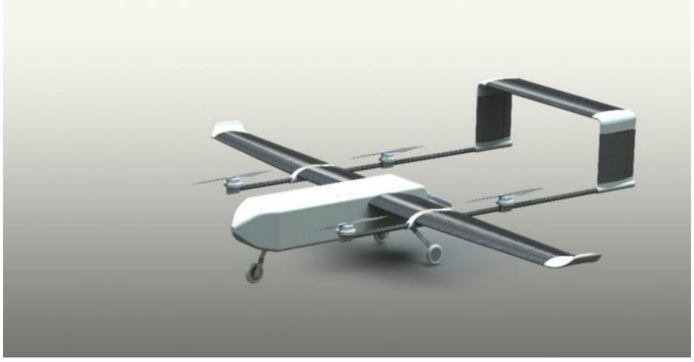

Fig. 2. Rendered image of the hybrid aircraft

Table 2. UAV aircraft specifications

Specifications	Value	Unit
Maximum take-off weight	33	kg
Core weight	25	kg
Maximum payload	8	kg
Hovering flight time	10	min
Flight time	30	min
Range	16	km
Size (l x h x w)	257 x 61 x 362	cm
Gliding speed	21	m/s
Stall speed	15.5	m/s

The aircraft's interior design and the package drop doors are visible in Figure 3. This aircraft has been designed to drop packages, which are small drones that can move to delivery locations as they are dropped from the aircraft. The designed package drone is shown in Figure 4.

Before manufacturing, we created a mathematical model that describes how the aircraft moves. This model includes factors like air resistance, wind, engine power, spinning parts, and gravity. With simulations, we verified its performance and designed algorithms to determine the best way to control it. Once the design was finalized, we created CAD drawings of all the parts.

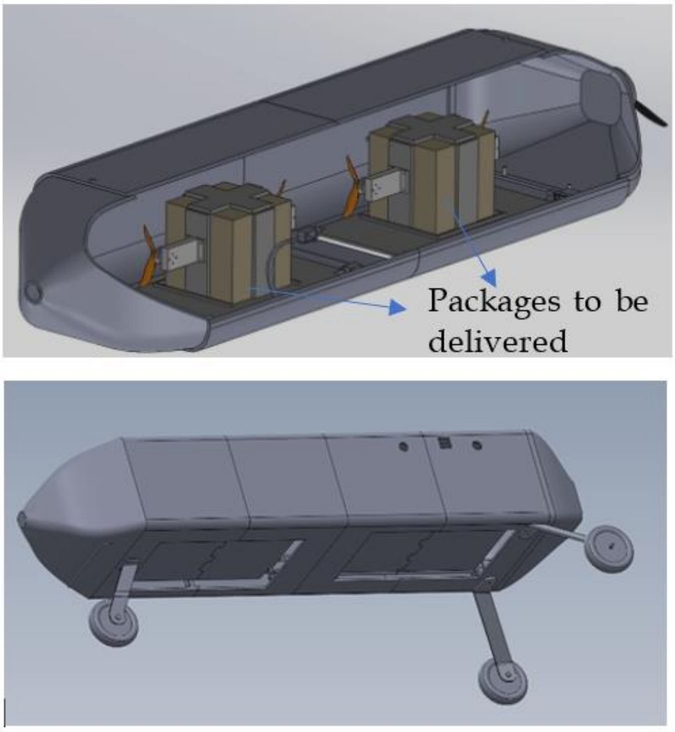

Fig. 3. Inside of the hybrid UAV aircraft body (up). The package-drop doors and landing gear (down).

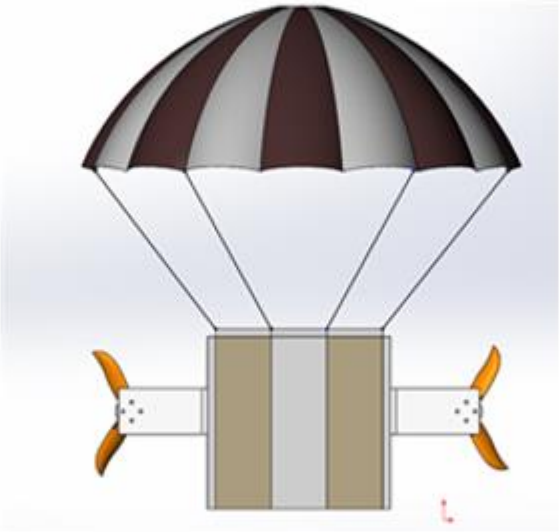

Fig. 4. Small package delivery drone to be carried inside hybrid UAV

3. Manufacturing of the Aircraft

Figure 5 presents the flowchart of the manufacturing and assembly steps of the aircraft. It involved composite manufacturing, mold manufacturing, 3D printing, and landing gear manufacturing.

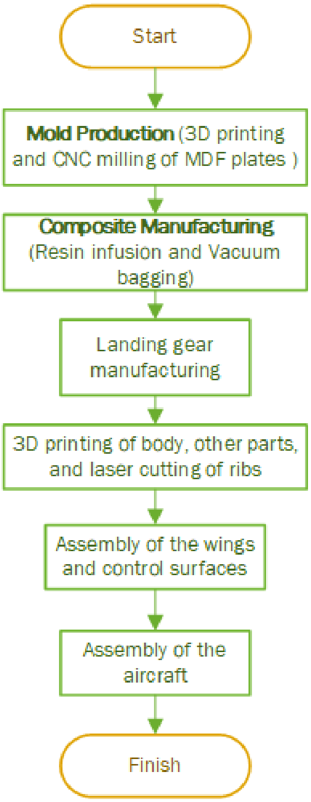

Fig. 5. Manufacturing and Assembly flowchart

3.1 Composite Manufacturing

Considering its strength and weight characteristics, carbon fiber is chosen as a reinforcement material over fiberglass. For carbon fiber-reinforced polymers (CFRP), there are numerous production methods available, including prepreg/autoclave procedures, vacuum infusion, vacuum bagging, and hand lay-up. Although prepreg/autoclave methods are frequently chosen in the industry to produce wings and bodies for a UAV, they are rather expensive in comparison to other approaches (McIlhagger et al., 2020). The product cannot obtain all of the details from the mold using the hand lay-up method, particularly where the leading and trailing edges are located. Contrarily, vacuum infusion offers an advantage over vacuum bagging since it vacuums extra resin out of the mold, greatly reducing the product's weight. Due to the high expense of prepping small parts for the vacuum infusion process, the aircraft's wings were created using vacuum infusion, while the control surfaces were produced using vacuum bagging.

Epoxy-based gelcoat set was obtained for gelcoat application to be used on the surface of the molds and produced composite shells. This set is used for higher surface hardness than other epoxy-hardener sets and can also be used for lamination purposes. The gelcoat application is performed by mixing hardener and lamination resin for about 5-10 minutes with a specified mixing ratio by the company which is the ratio of 100:40 in our case. Because the density of the hardener is lower than the resin, one must put the hardener in the mixing bowl first to mix the resin and hardener perfectly. Also, during the mixing operation, all walls of the bowl should be checked if there is an unmixed region in the mixture. Otherwise, after applying the resin, some parts may not cure completely. After the mixing process, the mixture should be kept waiting for degassing which is caused by the mixing process. If there is a vacuum pump and sealing equipment in the working environment, one can use the pump for the degassing process. Right after the mixing process, an exothermic reaction occurs in the mixture and when the temperature slightly rises relative to room temperature, the resin can be applied. The gelling duration is about 20 minutes for this type of gelcoat and the operation must be finished by that time. A Lamination set was obtained from the composite market for lamination and resin infusion processes. The mixing operation is similar to the gel coat application. For preparing lamination set to its application, the ratio is determined as 100:25. The gelling duration is about 2 hours for this type of resin which makes the resin applicable to resin infusion. Also, the viscosity is lower than the gel coat resin to reduce head loss while vacuuming the resin from the resin line to the vacuum line.

3.1.1 *Resin infusion process*

The resin is vacuum-drawn into a dry fiber laminate in a one-sided mold during the resin infusion process. The mold perimeter is covered with and sealed with a stiff or flexible film membrane. The method of resin infusion is regarded as a closed mold process. Relative to hand lay-up and vacuum bagging composite manufacturing techniques, this is more expensive in terms of material used, time, and labor work.

In Figure 6, the blue line is the vacuum line through which the resin is pulled to the catch pot (purple arrow), by the vacuum provided by the vacuum pump (blue arrow). The catch pot is connected to the vacuum line and the vacuum pump is connected to the catch pot with a PVC hose. The purpose of the catch-pot is to catch excessive resin for the pump to prevent damage. The red line is the resin line which the resin is fed into the mold. Also, the red arrow shows the sealing tape, also called gum tape. It is stuck to the mold and the bag so that it prevents air leakage.

Fig. 6. A normal setup for the resin infusion process

Detailed steps are as follows:

•Apply release agent to the mold. In this project, a PVA release agent is used. It is applied three times with 30-minute time intervals.

•Apply gum tape (bagging tape) around the mold.

•Place reinforcement material into the mold. The wing and tail composite shells are produced using three layers of reinforcement material.

•Tape or glue reinforcement material to hold it in its place. Taping can work for products with simple shapes. However, if there are any complex shapes or sharp edges on the product, it might be better to use spray adhesive to stick the reinforcement material on the mold. Also, using spray adhesive causes imperfections on the surface finish of the product.

•Cut, place, and tape a layer of peel-ply on reinforcement material. It should be cut to cover all areas between the bagging tape and should not be over-stretched.

•Cut and place infusion mesh around the size of the bagging tape. Infusion mesh is used to create a void in the mold to reduce head loss and if the mold is relatively large, the second layer of infusion mesh can be placed where the flow of the resin cannot be reached.

•Cut and place the infusion spiral on top of the infusion mesh. The infusion spiral is used for the same purpose as the infusion mesh. But, it has relatively more voids in it and resin can flow more easily inside of the spiral mesh. It is used to change the flow shape to a V-shaped flow.

•Cut and place the vacuuming mesh on the vacuum line. If the vacuuming mesh is unprocurable, then 2-3 layers of infusion mesh can be placed on the vacuum line. This step is necessary for flow to reach every spot on the vacuum line.

•Place and tape silicone connectors on the vacuum line and resin feed line.

•Cut the bagging film oversize to allow pleating. Pleats provide an extra surface so that bagging film can cover all surfaces on the mold. Otherwise over stretching of the bagging film occurs. In addition to this, in this process, the bagging film should be checked if there are any small holes in it.

•Stick the bagging film to the gum tape by stretching adequately to prevent any void between the bagging film and the gum tape.

•Cut PVC hose for resing feed line and vacuum line, circling gum tape 3-4 times at the end of the hose. Then place the vacuum clamps on the hoses.

•Cut a small hole in the bag where the inlets of the vacuum connectors are and connect the hoses to connectors on the resin feed line and vacuum line, by firmly pushing.

•Connect the hose for the vacuum line to the catch-pot and then connect the catch-pot to the vacuum pump. Catch-pot should already be leakage-free and it should have been tested already.

•Close air entry in the resin feed line by using the clamp.

•Evacuate the vacuum bag by using the vacuum pump. Then, the vacuum line must be closed by using another clamp, closing the PVC hose between the vacuum pump and catch-pot.

•Turn off the vacuum pump and check the sealing if there is any leakage on the setup. It can be followed by using the barometer on the catch-pot.

•If it is ensured that the mold is completely sealed, mix epoxy resin with its hardener. To allow excess resin in hoses and the catch-pot, the weight of the epoxy resin should be around 1.5 times of weight calculated regarding resin consumption of the reinforcement material.

•Allow the resin to degas for around 10 minutes.

•Turn on the vacuum pump and release the clamp on the resin feed line to start the infusion.

•Use the clamp to close the resin feed line when the resin reaches to catch pot.

•Wait around 10 seconds and then clamp the vacuum line.

•Turn off the vacuum pump and leave the part to cure for 24 hours.

In Figure 7 the catch-pot is shown after the process is complete. The catch-pot is sealed with gum tape, and a plastic container is placed inside it to collect excess resin and to prevent curing on the catch pot. Additionally, the vacuum pressure is around 700 mmHg, which is also used to check for any leakage in the bagging film.

Fig. 7. Catch-pot after the process is done

In the resin infusion process, after applying the release agent to the mold cavity, the reinforcement materials, peel ply, release film, and infusion mesh are positioned. Next, the spiral tubes are placed to achieve the desired flow shape. The setup, as illustrated in Figure 8(a), is completed by following the aforementioned steps. It is essential to establish a V-shaped flow to ensure complete wetting of all areas. The V-shaped flow is depicted in Figure 8(b) during the process.

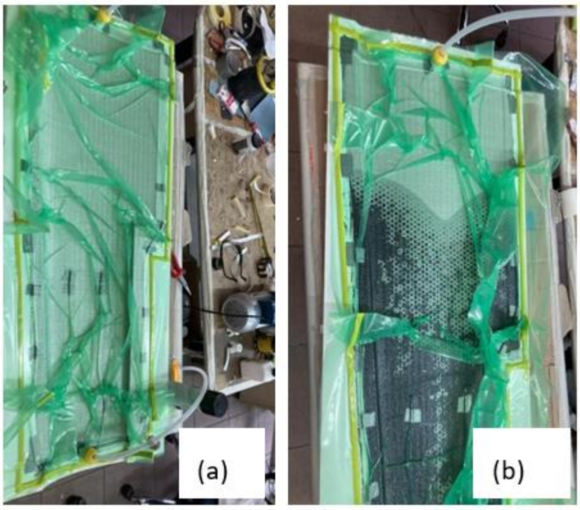

Fig. 8. Resin infusion process (a) Setup. (b) V-shaped flow

Finally, the setup is finalized by sealing the vacuum bag. To prevent excessive stretching of the bag, an appropriate number of pleats should be formed. Another crucial aspect is inspecting the sealing tape and vacuum bag for any leaks. Leak detection should be performed using a barometer located on the catch pot or a dedicated leak detector. If no leaks are found in the setup, the resin is prepared and degassed, and the infusion process is initiated by activating the vacuum pump. The resin flows from the feed line to the vacuum line. Once the resin reaches the vacuum line without any dry areas on the reinforcement material, clamps are applied to both lines to compress the tubes and maintain the vacuum after the process concludes (Figure 9(a)). In Figure 9(b), there are no dry areas present in the mold. The part is removed from the cavity once the resin has fully cured. Figure 10 illustrates the manufactured component.

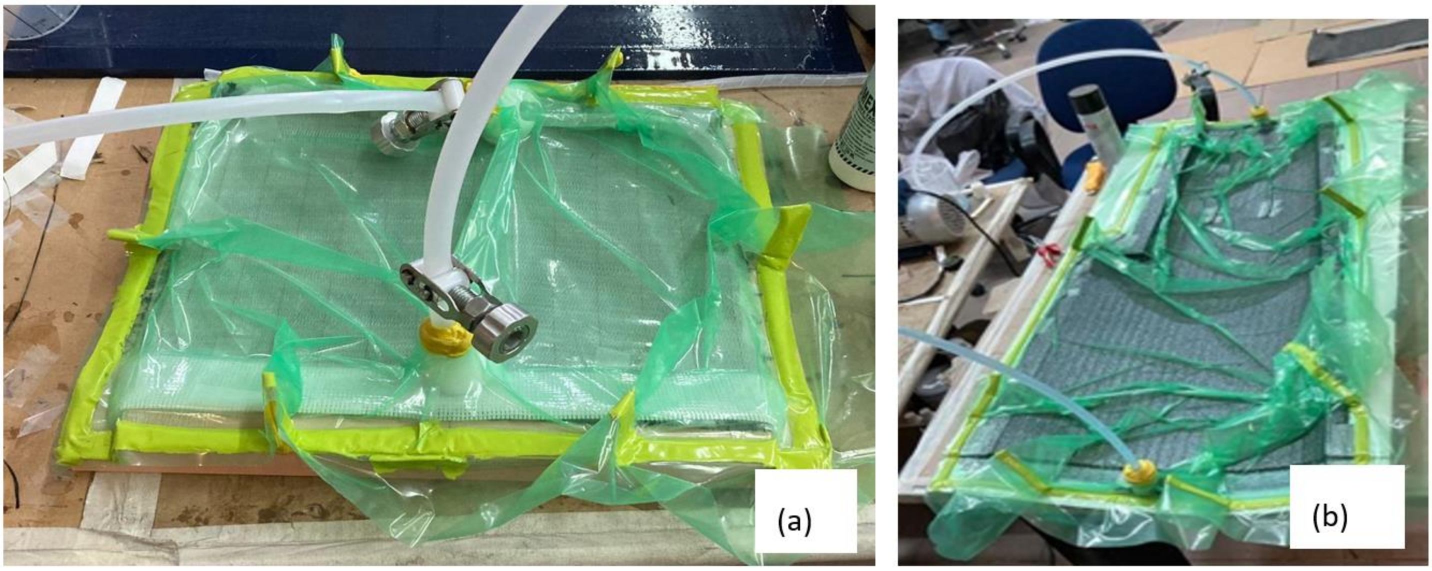

Fig. 9. (a) Curing another part. (b) Finished

Fig. 10. A composite shell part manufactured using resin infusion technique

While removing the product from the mold, one should be very careful not to damage the products. Even though the release agent is applied perfectly to the mold before the resin infusion, it can be very hard to remove the product, especially if the mold has sharp deep edges. One might use a spatula and wooden wedges to remove the product and slow down around sharp deep edges.

3.1.2 Hand lay-up

Hand lay-up is one of the easiest techniques in composite manufacturing. It is used when the parts to be produced do not have complex shapes and do not require lightness. In this paper, the process is used to produce composite shells of rudders. The process is explained as follows:

•Cut the desired number of reinforcement materials and one layer of peel ply. The size of the peel ply should be larger than the reinforcement material.

•Calculate the weight considering the resin consumption of the reinforcement material.

•Apply the release agent, as described in the previous section.

•Mix the resin with its hardener in an adequate ratio, as described in the previous section.

•Degassed for 10 minutes, and then, using a brush, wet all surfaces of the mold with resin where the reinforcement material will cover.

•Layer the first ply of reinforcement material on the mold and apply the resin on the reinforcement material with a brush. The pressure of the brush applied on the reinforcement material should be perpendicular to the mold to avoid displacing the reinforcement material.

•Repeat the previous step for the desired number of reinforcement material layers.

•Layer the peel ply on top of the reinforcement materials and apply pressure to the peel ply with a brush to remove excess resin.

•Leave the part to cure and remove it after 24 hours.

3.1.3 Vacuum bagging process

The vacuum bagging process is an extension of the hand lay-up technique. Before initiating the process, a bagging film is cut to a size that is double the dimensions of the mold. The film is then folded in half, and sealing tape is applied to the edges of the lower half. After applying the release agent and preparing the reinforcement materials, epoxy resin is applied using a brush, initially to the mold cavity and subsequently, layer by layer, to the reinforcement materials. The peel ply and breather are then placed on top of the reinforcement material, and the setup is sealed with bagging film and sealant tape (Figure 11). The breather is used to spread the vacuum throughout the mold. The pump is used to evacuate air, and a clamp is used to close the hose. Part cures in around 24 hours. After that, the component is removed from the cavity. The aileron and elevator parts are manufactured using this technique.

Fig. 11. Vacuum bagging process

3.1.4 Post-processing and assembly

After removing any parts from the mold regardless of which manufacturing technique is used, there will be some undesired sections on the edges of the product that should be removed before assembling them (Figure 11). Unwanted areas of composite parts are cut off and ground with a hand rotary tool once production is complete. Balsa plywood and carbon tubes form the main structure of the wings. A CNC laser cutting machine was used to cut the balsa ribs. The carbon tubes are then placed and, initially, glued to the ribs using epoxy adhesive to provide alignment for all of the ribs. After the epoxy adhesive is cured completely, the ribs are glued to the first composite shell. It will be useful to apply one layer of reinforcement material to the joint edges where it will be within the wing. Then, the second shell is attached to the ribs. If necessary, the connection edges must be ground down when the epoxy adhesive has fully dried.

In Figure 12, not only the structure of the main wings but also the assembly of the wings is shown. Because each side of the main wing consists of two sections and the second section is removable from the first section, they are connected to provide alignment for each section during the assembly process. Also, to make the assembly process easier, chamfers are created on the holes of the balsa ribs where the carbon-fiber tube profiles are inserted.

3.2 Mold design and manufacturing

Molds are used for CFRP manufacturing of wings, tail, and control surfaces. Two different techniques are used for mold manufacturing. Relatively small molds were produced using a 3D printer with PLA filament (Figure 13) to reduce time and material costs.

If a mold is bigger than the 3D printer volume, it is separated into pieces, manufactured, and combined afterward. Voids located at the joint edges are filled with polyester putty after it dries. Filling these voids is critical because epoxy gel coats are not thick enough to fill them, which can later cause leakages during the vacuuming process. Then, the whole mold is sanded until the height difference between each layer flattens and obtains a very smooth surface. This process starts with 80-grit sandpaper and progresses to 1000-grit. Finally, the mold is coated with a gel coat to make the composite shell surface smooth and shiny. The rudder mold after sanding and gelcoat process is shown in Figure 14.

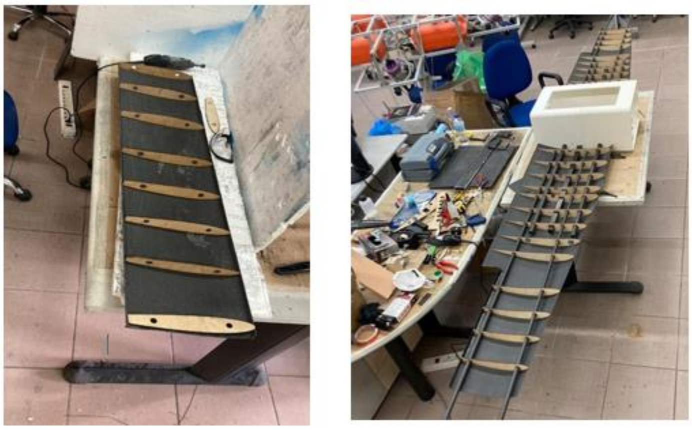

Fig. 12. Assembly of the horizontal tail wing and the main wing

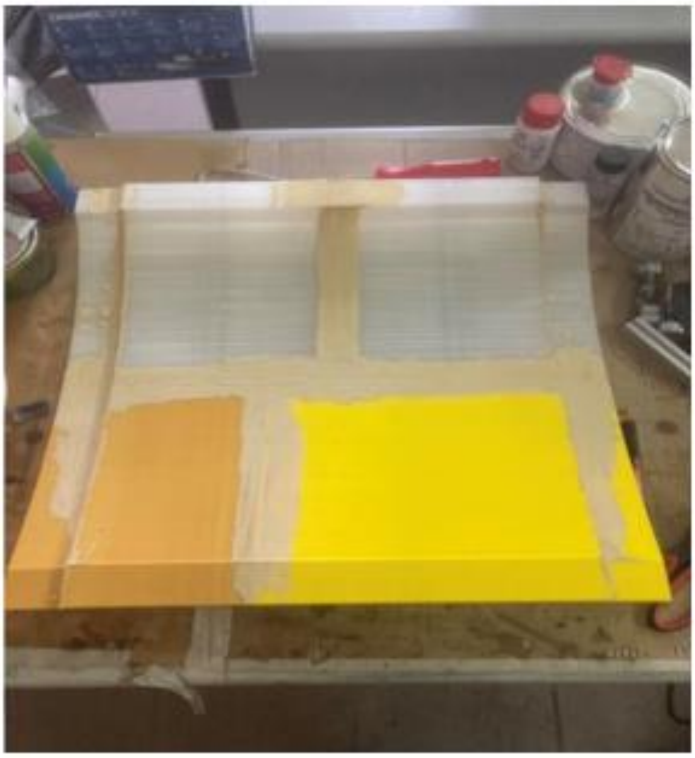

Fig. 13. 3D printed mold

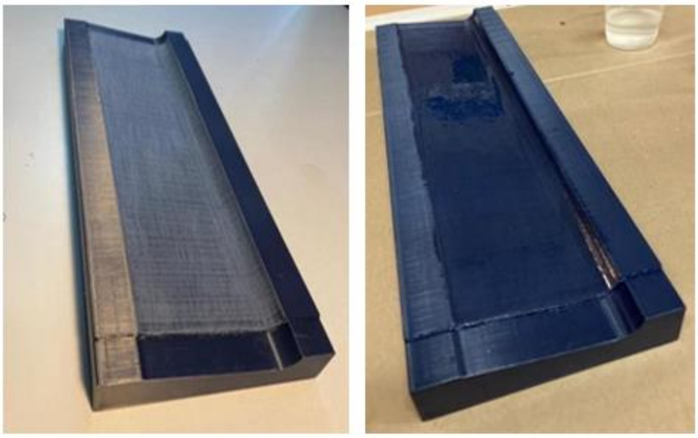

Fig. 14. Rudder mold: (a)After sanding. (b)After gelcoat

Additionally, significantly bigger molds are manufactured by processing laminated medium-density fiberboard (MDF) wood (Figure 15). For this process, MDF wood plates should first be laminated. MDF plates are stacked to the desired height while gluing them to each other with wood glue. Plates are held for 24 hours to allow the glue to dry. Then, they are processed with a CNC milling cutter. The MDF molds should be varnished as soon as possible to avoid swelling due to moisture. Once the varnish dries, the paintwork operation can be started. The raw surface of the molds is sanded until it is very smooth, gradually increasing the grit number of the sandpaper at each step. Then, acrylic paint is applied to the mold. After it dries, the painted surface is sanded again. This process is repeated until the paint reaches six or more layers. For the final layer, the paint should be sanded with a 3000-grit number sandpaper until the surface is shiny. Once it gets to this state, wax polish is applied to the mold's painted surface with a piece of cotton or cloth. Since this process will erode the paint a little bit, it must be ensured that the paint thickness is enough for wax polishing. After wax polishing, the molds should be glossy.

3.3 3D Printing (AM)

The 3D printing technique is widely used in the manufacturing of wing and tail connection parts, body panels, brushless direct current (BLDC), servo motor connection parts, molds, etc. (Figure 16). All the parts are manufactured using an FDM 3D printer with a PLA filament. A Creality CR-10S4 3D printer at the laboratory was used for manufacturing. The parts were designed using the Solidworks CAD program. Subsequently, the part files were converted to stereolithography (STL) files. The STL files were sliced into layers, and then Gcode files were obtained for manufacturing using the Cura program. To maximize the payload, the prototype must be lightweight but durable enough to withstand impact forces during landing. Parameters were set to keep a balance between these specifications. Octoprint was used as a 3D printer interface on a Raspberry Pi computer. This allowed prints lasting more than a day to be monitored over the Internet.

In this study PLA and light weight polylactic acid (LWPLA) materials were used for additive manufacturing. Table 3 shows the comparison between PLA and LWPLA. PLA material is mostly used for molds, fittings, and other parts that require strength. On the other hand, LWPLA material is used for fuselage panels, horizontal tail connection parts, etc. LWPLA may form bubbles at a rate that varies depending on the printing temperature. As the temperature increases, the amount of bubbles increases; therefore, the density of the part changes. The weight can be reduced by up to 65% compared to the same volume without foam. This approach reduces the weight compared to regular PLA, but also decreases strength. This material has a density of 0.4 to 1.24 g/ cm^3 and a glass transition temperature of 55 to 60 °C. To optimize the three parameters mentioned above, the tip temperature was set to 235 °C, and the flow rate was set to 45%. Extrusion temperature, layer height, print speed, and infill density were selected to achieve strong interlayer bonding and strength. Since LWPLA material is expensive, it is only used when necessary.

Table 3. Comparison table between standard PLA and LWPLA

Property	Standard PLA	LWPLA
Density	~1.24 g/cm³	~0.4–1.24 g/cm³
Tensile Strength	~50 MPa	~30-40 MPa
Impact Strength	Moderate	Low to moderate
Print Temperature	190–220°C	200–260°C
Weight Reduction	None	Up to 65%

Fig. 15. MDF wood molds after CNC milling (left). After varnishing and paintwork (right)

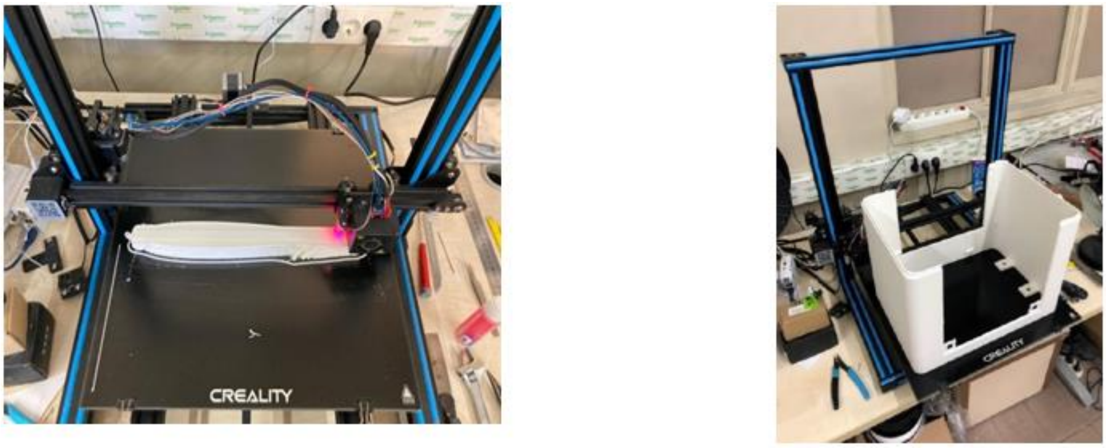

Fig. 16. 3D printing of winglets (left) and the aircraft body (right)

Most of the 3D parts were used as a mold for composite manufacturing. The durability and strength of these parts were considerably high. Some smaller parts on the aircraft such as package doors were made with PLA. Their strength and durability were acceptable for the application. To speed up the manufacturing process, and to lower the weight of the aircraft we used LW-PLA as aircraft body material. Although its tensile strength depends on foam selection, it is in the range 30-40 MPA (lower than standard PLA). We determined that the LW-PLA is not suitable for structural or load-bearing components, and for high-temperature applications. We added additional carbon rods along the body to increase the structural integrity

3.5 Manufacturing Landing Gear

The landing gear was designed to be manufactured from aluminum 6061. It is designed by inspiring fixed-wing aircraft so that it would also have the ability to land on a runway. Considering the potential stress in usage and the weight of the landing gears, a suitable value of 6 mm was selected as the thickness of the landing gear. Plates are cut by a CNC laser cutting machine, and then they are bent by a folding machine with a 6.5 mm cavity. In the design, some elliptical holes are made to make the landing gear lighter. Also, three aluminum shafts are manufactured using a turning lathe for landing gear (Figure 17). The tires are installed on the shaft using stoppers.

3.6 Assembly of the Aircraft

The carbon-fiber composite shell of all aerodynamic surfaces (main wing and tail wing parts, control surfaces) is assembled by positioning balsa ribs inside the composite shell. The structure of the aircraft, which provides rigidity and strength, is made of carbon fiber profiles and balsa profiles assembled inside composite shells mounted on the carbon-fiber structure (Figure 18). The propulsion system and other actuators like servo motors are mounted on wings and structures using 3D printed parts. Carbon fiber profiles are used throughout the aircraft's structure to ensure lightness. These products are produced by the pultrision method and are relatively strong materials. The largest profile is a tail beam with a 30 mm diameter tube. It is deliberately selected to avoid buckling on the wing structure while controlling yaw angle and rate. Additionally, the main wing is supported by two circular, 24 mm diameter and one 30x30 mm square CFRP profile along the body and the first two sections of the wings. The second sections of the wings and tail are supported using 16 mm and 12 mm diameter circular tube profiles, respectively. To make the aircraft as portable as possible, the second sections of the wings, the entire tail, and the tail beams are designed to be removable.

Figure 19 presents the wings, tail, body, and other parts to be assembled into the aircraft. The motor, propellers, servos, and other electronic elements are assembled in Figure 20.

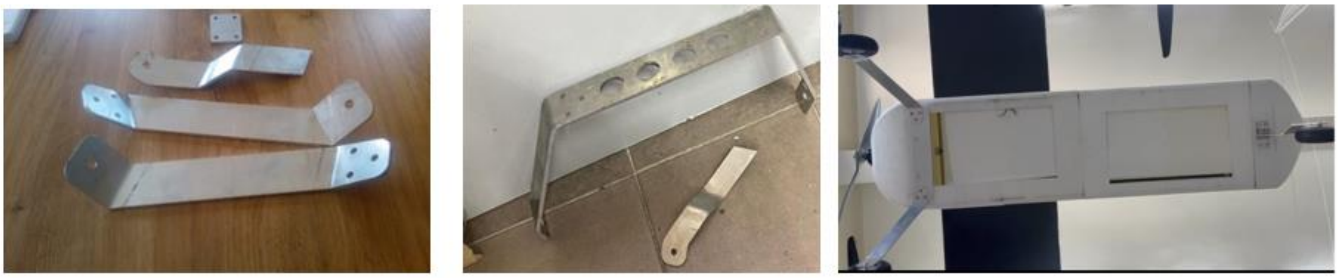

Fig. 17. Landing gear. Version-1 (left). Version-2 (middle), Installed landing gear (right)

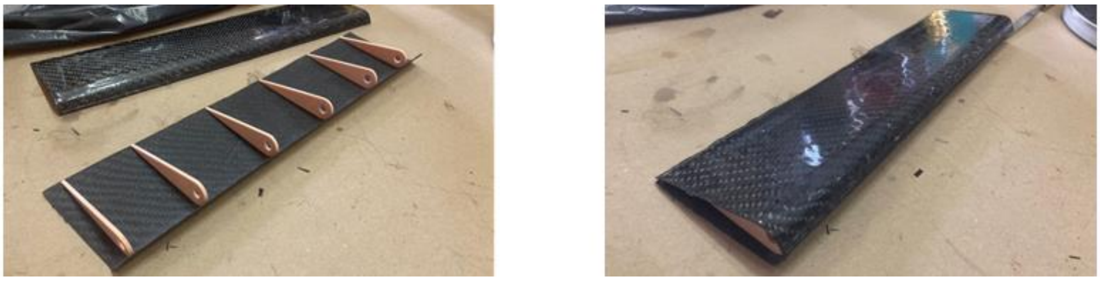

Fig. 18. The horizontal tail wing's assembly steps

Fig. 19. The Hybrid UAV in the assembly phase (left). Partially assembled plane (right)

Fig. 20. Manufactured Hybrid UAV prototype, with wings and electronics

4. Final Remarks

Table 4. Delivery cost and delivery times comparison

Cost and time for delivery of packages (TL, minutes or hours)	Proposed UAV	Delivery by Car (need to consider return time and cost)	Cargo Company
Single 4 kg package	4TL, 10 min	266TL, 30-60 min	340TL, 24 hours
Two 4 kg packages at the same location	4TL, 10 min	266TL, 30-60 min	421TL, 24 hours
Two 4 kg packages at two different locations (1km apart)	4TL, 12 min	280TL, 30-60 min	680TL, 24 hours

The proposed system offers benefits in two key aspects: the cost saving and flexibility due to the proposed manufacturing approach and the savings on delivery time and costs.

The manufacturing cost of the system was approximately 15,000 EUR (as of 2023), including material, electronics, and personnel costs. We obtained a price quote for manufacturing the composite wings and control surfaces at a discounted rate of 22,000 EUR. It is expected that if we had opted for traditional manufacturing, the prototype would have cost at least two to three times more.

Unlike previous work that requires time-consuming UAV landings and take-offs for package delivery, this work proposes a hybrid UAV and intelligent packages for targeted package delivery. Moreover, the aircraft can carry two packages simultaneously. This approach results in significant benefits in terms of delivery time and cost. Considering the initial design criteria for making deliveries between the faculty building and the main library (7.78 km), Table 4 presents the advantages of the proposed system. With a 12S LiPo battery that has a 20Ah capacity, an %85 charging efficiency, and an energy cost of 3.11TL/kWh, the energy cost per delivery is estimated to be approximately 4TL. The system can be ready for a new delivery within 25 minutes using a battery swap. The system is superior in both delivery cost and delivery time

5. Conclusions

This study explores the potential of AM combined with composite manufacturing techniques for rapid manufacturing of a 3.8-meter wingspan hybrid UAV. The system consists of a hybrid aircraft and a parachute drone to be delivered. After explaining the goals of the aircraft, the aerodynamic and mechanical design to develop a UAV has been explained. The manufacturing techniques involved both FDM printing and composite manufacturing. The aircraft body, as well as molds for producing wings, were fabricated with a 3D printer. Control surfaces were manufactured using the vacuum-infusion method. Post-processing operations and assembly of the aircraft are explained. Built prototype has been used in experiments, and determined to be a reliable aerial platform.

The primary advantage of additive manufacturing (AM) lies in its ability to create lightweight, optimized structures that maintain or enhance strength and performance while minimizing the number of components required. During the research and development phase, this technology facilitated faster design iterations and enabled rapid manufacturing. By reducing the need for multiple parts and minimizing material usage during production, AM significantly reduces waste and contributes to a lower environmental impact. The findings of this study indicate that even large-scale aircraft can be built with this approach. Our future work will involve outdoor experiments focusing on algorithm development and system integration.

The novelties of the paper are as follows:

- This work presents a novel approach to UAV cargo delivery. Unlike previous work that requires time-consuming UAV landings and take-offs for package delivery, this work proposes a hybrid UAV and intelligent packages for targeted package delivery. Moreover, the aircraft has been designed to carry two packages at a time. This approach promises accurate and fast package delivery.
- Although there are some aircraft that were built with AM, this work demonstrates that it is possible to manufacture a bigger 3.8-meter wingspan hybrid UAV, using standard laboratory resources. Therefore, it highlights the potential of combining AM with traditional composite manufacturing techniques to produce complex UAV components.
- This work provides a detailed account of the UAV development process, including the design, manufacturing, and assembly phases, which could be useful as a reference for other researchers.
- The work presents findings confirming the reliability of the 3D-printed UAV as a robust platform, suggesting that 3D printing can make UAV manufacturing more accessible and efficient, potentially accelerating the advancement of UAV technologies.

CRediT Author Statement

Turan Konyalıoğlu: Analysis, Manufacturing, Design, Coding, Experimentation, and Paper writing. **Sinan Alnıpak:** Design and Manufacturing. **Halil İbrahim Şahin:** Manufacturing. **Erdinç Altuğ:** Analysis, Managing research, Locating funding, Analysis, and Paper writing.

Nomenclature

AM	: Additive Manufacturing
BLDS	: Brushless Direct Current
CFD	: Computation Fluid Dynamics
CFRP	: Carbon-fiber reinforced polymer
CNC	: Computer numerical control
FDM	: Fused Deposition Modelling
LW-PLA	: Light Weight Polylactic Acid
MDF	: Medium-density fiberboard

PLA	: Polylactic acid
UAV	: Unmanned Aerial Vehicle
VIP	: Vacuum Infusion Process
VLM	: Vortex Lattice Method
VTOL	: Vertical Take-off and Land

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Research Article

Investigating the Relationship Between ESG Performance and Efficiency in Aircraft Manufacturers

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Abstract

This study examines the relationship between operational efficiency, market efficiency and ESG (Environmental, Social and Governance) performance of publicly traded aircraft manufacturers. As a contribution to the literature, this research provides a novel efficiency analysis of aircraft manufacturers and applies wavelet methodology to the investigation of ESG-efficiency relationships in aviation. For the period 2003¬–2023, manufacturers' efficiency was analyzed using Window Network DEA, which effectively addresses the limited number of industry decision makers. In the second stage, wavelet analysis was used to examine the relationships between efficiency outcomes and ESG scores, which has the advantage of revealing temporal relationships without requiring cointegration tests. The results show that the correlation patterns between manufacturers' efficiency and ESG scores exhibit temporal variations, with strong correlations (0.7-0.9 coherence) consistently observed over 10–15-year periods. Specifically, strong relationships were found between Airbus' operational efficiency and ESG performance in 3–4-year cycles, and between Boeing's marketing efficiency and ESG performance in the 8–15-year range. These findings suggest that ESG integration requires a long-term strategic approach that goes beyond the short-term focus prevalent in the existing literature. From a managerial perspective, the impact of ESG integration varies across firms depending on factors such as size, market segmentation and operational context, suggesting that ESG strategies should be tailored to specific firm characteristics. This research contributes to the growing aviation sustainability literature by providing unique insights into the long-term relationships between ESG and efficiency in an oligopolistic market.

Keywords

Aviation
ESG
DEA
Sustainability
Wavelet

Time Scale of Article

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1. Introduction

This study examines the relationship between the efficiency and sustainability performance of aircraft manufacturers operating in the global aviation industry. Operational efficiency measures how efficiently companies use their resources (labor, capital, technology), while marketing efficiency assesses the extent to which this operational efficiency translates into financial performance and market value. Environmental, Social and Governance (ESG) scores are a holistic sustainability assessment that measures a company's environmental impact, social responsibility, and corporate governance structures. This study analyzes how aircraft manufacturers' performance in

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these three areas influence each other and how they change over time. The findings should provide valuable insights for managers, investors and policy makers seeking to understand the impact of sustainability strategies on operational and financial performance. This study uses the Window Network DEA methodology to deal with the limited sample size in the industry. Wavelet analysis is used to identify time-varying relationships without the need for stationarity assumptions.

Increasing global climate events in recent years have highlighted the need for the international community to pay more attention to the challenges posed by natural disasters. In this context, sustainable and green development planning has emerged as a key objective for many countries, aiming to minimize potential conflicts between economic growth and environmental protection.

The ESG concept was first introduced in the 2006 United Nations Principles for Responsible Investment (UN PRI) report, establishing itself as a non-financial corporate rating system that integrates environmental, social and governance factors into investment decisions (Ji et al., 2023). This scoring framework comprises three fundamental components: The environmental (E) component measures the environmental impacts of the company, such as carbon emissions, energy efficiency, waste management and natural resource use. The Social (S) component assesses the fulfilment of social responsibilities such as human rights, labor practices, community relations and product stewardship. The Governance (G) component focuses on the corporate governance structure, such as board composition, executive compensation, audit practices and transparency. The integration of these components, particularly in capital-intensive industries such as aviation, demonstrates different levels of accountability that affect an organization's long-term growth trajectory and financial sustainability (Fang-Chen Kao et al., 2022). ESG scores have emerged as fundamental indicators for evaluating corporate sustainability and represent a significant tool for integrating the United Nations' Sustainable Development Goals (SDGs) into financial investments (Clément et al., 2022). Accordingly, ESG scores have become an integral component of corporate sustainable growth strategies. As Pham et al. (2022) emphasize, these scores aim to extend corporate lifecycles, enhance social engagement, and strengthen investor confidence.

From an economic sustainability perspective, productivity and efficiency in the use of resources and technology are critical to sustaining and advancing growth trajectories (Irwin and Pavcnik, 2004). This paper examines two types of efficiency: operational efficiency and market efficiency. Operational efficiency refers to the efficiency with which a firm converts inputs (resources such as capital, labor, raw materials) into outputs (aircraft produced, orders completed) and includes the optimization of production processes, supply chain management and resource allocation. Marketing efficiency measures the firm's ability to translate operational success into market value, shareholder returns and competitive advantage, and reflects the efficiency of marketing strategies, market positioning and investor relations. While in the 20th century the maximization of production factors was considered sufficient, today's conditions require a more comprehensive approach and the sustainability of economies and national resources has emerged as a fundamental evaluation criterion (Budd et al., 2013). Although the financial position of civil aviation sector enterprises has shown improvement following the recent global financial crisis and pandemic, cost and resource efficiency continue to maintain precedence on the sector's management agenda. Within this economic framework, international and national civil aviation authorities must integrate environmental considerations into their strategic planning to ensure sustainable aviation operations (Guimarans et al., 2019).

In response to these challenges, the International Civil Aviation Organization (ICAO), as the premier authority in civil aviation, has established a stakeholder forum through its Global Coalition aimed at fostering innovative solutions and reducing greenhouse gas emissions (ICAO). This initiative is designed to contribute to the development of long-term environmental objectives and implementation measures for the international aviation sector (Alpman and Göğüş, 2017; Öztürk and Göktepe, 2024). The ICAO Global Coalition continues its carbon emission reduction efforts in coordination with CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), pursuing the goal of sustainable aviation. Carbon emissions represent one of the most significant environmental challenges facing the contemporary aviation industry, highlighting the multidimensional nature of sustainability challenges within the sector. As Pham et al. (2022) note, the energy requirements for production capacity development, the resources utilized in energy production, and their potential ecological impacts have reached levels threatening global environmental balance. Consequently, sustainability performance metrics, particularly for publicly traded companies, are now measured through indices and reported to stakeholders.

The primary objective of this study is to analyze the operational and market efficiency of aircraft manufacturers between 2003 and 2023, with a specific focus on examining the relationship between manufacturers' efficiency scores and ESG performance.

This analysis aims to contribute to our understanding of how sustainability metrics correlate with operational efficiency in the aviation industry.

2. Literature Review

The literature review is divided into two parts. Initially, studies on airlines and aircraft manufacturers' markets are reviewed. Second, studies which focus on application of DEA approaches.

The deregulation of the aviation industry started from the USA in the 1970s and then expanded to the other countries. With this development, the aviation industry began to gain importance, especially in the USA (Goetz and Vowles, 2009). In this process, the United Kingdom and the European Union followed the leading countries with their development in globalizing economic relations. It is observed that this has created an effect of other countries catching up with the liberalized countries in this industry (Dobson, 2017). Although the liberalized civil air transportation industry has made it necessary for different business models to emerge in the airline industry, it has also allowed people to use the fastest means of transportation at affordable prices (Whyte and Lohmann, 2016). The need to focus on low costs due to increasing competition conditions has also allowed the increase of private equity initiatives in the air transport industry. As a result of these developments, the air transport industry has developed on a global scale in terms of both the number of airline operators and the number of passengers carried (Williams, 2017; Efthymiou and Papatheodorou, 2018). Similar developments have not been made at the same level among manufacturers producing aircraft for civil air transportation. Technological developments have had a positive impact on both operators and aircraft manufacturers. However, the number of aircraft manufacturers has remained limited within the framework of market structure development (Golich, 1992; Kronemer and Henneberger, 1993). Airbus and Boeing dominate the market for commercial aircraft manufacturers, but other manufacturers like Embraer and Bombardier are also preferred for regional flights (Pingle, 2024). The emergence of a small number of producers or firms in capital-intensive industries is considered as normal (Hasan et al., 2013; Judzik and Sala, 2015). Nevertheless, it would be useful to examine the efficiency and analyze the situation of these firms in imperfectly competitive markets.

It is important for businesses to use their resources productively and effectively in order to continue their activities. Therefore, as in other industries, efficient and effective operations in the aviation industry are necessary for airlines to continue their economic activities. There are many studies on this field within the scope of civil air transportation in the aviation industry. These studies will be evaluated globally and regionally, and current approaches will be stated without regional distinction. First of all, studies show that classical data envelopment analysis (DEA) and total factor productivity methods are widely used in studies examining international airlines (Barbot et al., 2008; Merkert and Hensher, 2011; Arjomandi and Seufert, 2014; Lee and Worthington, 2014; Kottas and Madas, 2018). The common features of these studies are as follows: conducting operations in a business model that reduces costs and establishing partnerships that will increase capacity utilization positively affects productivity and efficiency. When regional studies are evaluated, it is seen that studies in this field have started earlier and differences in methods have emerged. Most of the studies covering the American and European regions consist of classical DEA studies. These studies include total factor productivity and other indexed DEAs (Graham et al., 1983; Distexhe and Perelman, 1994; Good et al., 1995; Alam and Sickles, 1998; Fethi et al., 2000; Alam et al., 2001; Carlos Pestana Barros and Peypoch, 2009; Assaf, 2011; Carlos Pestana Barros and Couto, 2013; Carlos P Barros et al., 2013; Duygun et al., 2013; Voltes-Dorta et al., 2024). In addition, there are studies that have analyzed these regions using two-stage and network DEA methods (Gramani, 2012; Lu et al., 2012; Mallikarjun, 2015; Wanke et al., 2015; Duygun et al., 2016; Wanke and Barros, 2016; Khezrimotlagh et al., 2022; Kaffash and Khezrimotlagh, 2023). A small part of the studies covering Asia and Africa consists of classical DEA frameworks (Chiou and Chen, 2006; Qian Cao et al., 2015; Jain and Natarajan, 2015; Zhongfei Chen et al., 2018; Sakthidharan and Sivaraman, 2018). There are more studies that have examined the liberalization process in the aviation sector using two-stage and network DEA methods in these regions, which were enacted later than the United States and Europe (Carlos Pestana Barros and Wanke, 2015; Wanke et al., 2015; Zhongfei Chen et al., 2017; Mhlanga et al., 2018; Soltanzadeh and Omrani, 2018; Chia-Nan Wang et al., 2019; Hang Yu et al., 2019; Ming-Miin Yu and See, 2023; Ming-Miin Yu and Rakshit, 2024). It is observed that the use of multi-stage DEA method is increasing as a current approach. It is stated that multi-stage analysis allows detailed analysis of processes (Doğan et al., 2024). While there are comprehensive studies on airlines, there appears to be no study on productivity and efficiency for commercial aircraft manufacturers. This is thought to be due to the limited number of companies in the aircraft manufacturing industry.

Although there are extensive studies on airlines, it is seen that there is no study within the scope of productivity and efficiency for commercial aircraft manufacturers. It is considered that the reason for this situation is the limited number of companies in the aircraft manufacturing industry. Today, DEA method is used in industries within imperfect competition conditions. It is seen that window DEA methods are used in industries such as banking, electricity distribution, health services, logistics, iron and steel, air transportation (Asmild et al., 2004; Halkos and Tzeremes, 2009; Chia-Nan Wang et al., 2019; Zarbi et al., 2019; Zhou et al., 2020; Miszczynska and Miszczyński, 2022; Nam Hyok Kim et al., 2023; Doğan et al., 2024). This study aims to contribute to the literature by applying the Window Network DEA method to commercial aircraft manufacturers, using previous applications in related industries as a reference.

Studies examining the relationship between ESG performance and firm efficiency have increased in recent years. Regarding the strategic benefits of ESG integration in capital-intensive industries, Buallay (2019) demonstrates the positive impact of ESG practices on financial performance in the banking sector; similarly, Lujie Chen (2015) finds that sustainability improves firm performance in the manufacturing sector. In terms of how ESG practices affect operational efficiency through risk mitigation, cost reduction and stakeholder trust, Qiang Cao et al. (2024) find that ESG investments in Chinese banks improve operational efficiency. Bin Wang et al. (2025) find that ESG performance of Chinese companies has a positive impact on technical efficiency, especially in the long run. In aviation and related industries, Voltes-Dorta et al. (2024) found that sustainability targets improve the efficiency of airlines, while Ji et al. (2023) assessed the impact of ESG on the technical efficiency framework under competitive conditions. Although these studies show that ESG affects financial performance, there are few studies that examine the temporal and structural effects of ESG components on the operational and marketing efficiency of aircraft manufacturers, especially in oligopolistic markets like aerospace, where long-term impacts are particularly important. This study aims to fill this gap in the literature by revealing the dynamic nature of these relationships using wavelet analysis.

Firms are expected to be not only economically efficient but also good at sustainability (Chang, 2015). Therefore, it has become necessary for countries to be sensitive to environmental issues as well as productivity and efficiency while aiming for economic development (Bojnec and Papler, 2011; Dong et al., 2015; Anis et al., 2023). In this framework, the creation of ESG scores by Thompson Reuters Refinitiv (2023) and the effects of these scores on firms have started to be investigated in several industries (Tarmuji et al., 2016; Yoon et al., 2018; Ionescu et al., 2019; Ersoy et al., 2022; Pham et al., 2022; Iazzolino et al., 2023; Voltes-Dorta et al., 2024). Pham et al. (2022), Iazzolino et al. (2023) and Voltes-Dorta et al. (2024) have examined the relationship between ESG scores and business performance and market values with different approaches. In this study, it will be evaluated with a similar approach.

3. Method

The data used in this study were obtained from Reuters Refinitiv Eikon platform. This study utilizes two different methods. In the first stage, the efficiency of listed aircraft manufacturing firms operating in the aircraft manufacturing industry will be analyzed with two-stage (operational efficiency and market efficiency) Network Data Envelopment Analysis (DEA). This model is based on Chiang Kao and Hwang (2008), Chiang Kao and Hwang (2010) and Doğan et al. (2024). The two-stage model is particularly appropriate for this study as it allows for a clear separation between the operational processes and the market outcomes, which is crucial for understanding the impact that ESG factors might have on different aspects of a company's performance. The general framework of the input-oriented, constant returns to scale and 2-stage serial network DEA model is as follows:

$$\mathrm{E_k} = \max \textstyle\sum_{r=1}^{s} \upsilon_r \times \mathrm{Y_{rk}} \tag{1}$$

E_k represents the efficiency score of the kth Decision-Making Unit (DMU)

U_r is the weight assigned to output r

Y_{rk} is the value of output r for the kth DMU

$i: Inputs\ (i = 1, \dots, m)$

$r: Outputs\ (r = 1, \dots, s)$

$p: Intermediate\ Output/Input\ (p = 1, \dots, t)$

$j: DMU\ (j = 1, \dots, n)$

Constraints:

$$\textstyle\sum_{i=1}^{m} \nu_i \times \mathrm{X_{ik}} = 1 \tag{2}$$

$$\textstyle\sum_{r=1}^{s} \upsilon_r \times \mathrm{Y_{rj}} - \sum_{i=1}^{m} \nu_i \times \mathrm{X_{ij}} \leq 0\,,\ j = 1, \dots, n \tag{3}$$

$$\textstyle\sum_{p=1}^{q} \mathrm{W_p} \times \mathrm{Z_{pj}} - \sum_{i=1}^{m} \nu_i \times \mathrm{X_{lj}} \leq 0\,,\ j = 1, \dots, n \tag{4}$$

$$\textstyle\sum_{r=1}^{s} \upsilon_r \times \mathrm{Y_{rj}} - \sum_{p=1}^{s} \mathrm{W_p} \times \mathrm{Z_{pj}} \leq 0\,,\ j = 1, \dots, n \tag{5}$$

$\mathrm{U_r}, \nu_i, \mathrm{W_l} \geq \varepsilon$ and $r = 1, \dots, s;\ i = 1, \dots, m;\ p = 1, \dots, q$

Efficiencies:

$$\mathrm{E_k^{1.Stage}} = \frac{\sum_{p=1}^{q} \mathrm{W_p} \times \mathrm{Z_{pk}}}{\sum_{i=1}^{m} \nu_i \times \mathrm{X_{ik}}} \tag{6}$$

$$\mathrm{E_k^{2.Stage}} = \frac{\sum_{r=1}^{s} \upsilon_r \times \mathrm{Y_{rk}}}{\sum_{p=1}^{q} \mathrm{W_p} \times \mathrm{Z_{pk}}} \tag{7}$$

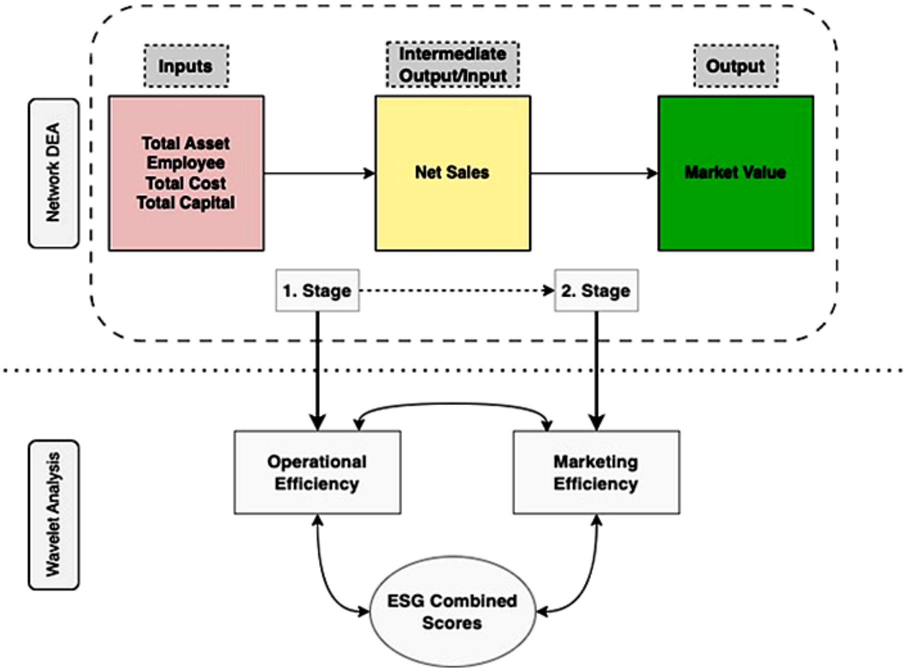

Figure 1 Summary of Methodology

Given the limited number of firms in the aircraft manufacturing market, Window analysis was integrated into the Network DEA methodology to enhance the robustness and comprehensiveness of efficiency measurements. This methodological framework builds upon the theoretical foundations established by Charnes et al. (1983) and incorporates the implementation model developed by Halkos and Tzeremes (2009). Following Asmild et al. (2004) empirical findings, a three-period window width was adopted. This methodological integration enables a rigorous efficiency analysis of the oligopolistic market structure characterizing the aircraft manufacturing sector.

In the second step, the relationship between the operational and market efficiency of the aircraft manufacturers and the ESG composite score is examined. Wavelet analysis is used to determine this relationship. Wavelet analysis is the preferred method for analyzing periodic events in a time series and the way in which these events change over time. In contrast to traditional cointegration analysis, wavelet analysis can show how the relationships between variables change over different time periods and at different frequencies. It can decompose the effects of factors such as economic shocks and industry dynamics, making it ideal for analyzing long-term financial and operational data. The absence of stationarity requirements makes this method more robust to the analysis of the aviation industry, which is subject to significant cyclical patterns and structural changes, than traditional time series approaches (Ramsey and Lampart, 1998; Kyung Hwan Kim and Kim, 2003; Fan and Gençay, 2010; Paç and Öner, 2024). For this, the WaveletComp package was used in the R program (Rösch and Schmidbauer, 2016). The following steps are followed in Wavelet analysis:

1. Step

$$\varphi(t) = \pi^{-1/4} e^{i\omega t} e^{\frac{-t^2}{2}}$$

2. Step

$$W_x(\daleth, S) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{S}} \psi^*\left(\frac{t-\daleth}{S}\right) dt$$

3. Step

$$Power(\daleth, S) = |W_x(\daleth, S)|^2$$

4. Step

$$W_{xy}(\daleth, S) = W_x(\daleth, S). W_y^*(\daleth, S)$$

5. Step

$$Coherency(\daleth, S) = \frac{|W_{xy}(\daleth, S)|}{\sqrt{|W_x(\daleth, S)|^2 . |W_y(\daleth, S)|^2}}$$

6. Step

$$Angle(\daleth, S) = \arg\left(W_{xy}(\daleth, S)\right)$$

By performing the aforementioned steps in Wavelet analysis, the need to test for stationarity in the data can be eliminated. Wavelet analysis, which reveals the strength of effects at different frequencies, provides an opportunity to analyze both the strength and direction of interactions between variables by distinguishing across two dimensions – time and frequency (Ramsey, 2002; Crowley, 2007). The wavelet analysis approach emerges as a particularly effective method due to its ability to differentiate between the spectral properties of unit root processes and short-memory stationary processes. This analytical technique's distinctive advantage lies in its capacity to decompose the spectral behavior of these processes. The methodology's robust capability to handle such decomposition, combined with its ability to capture temporal variations in relationships, makes it particularly suitable for the present study. In addition, interpreting the analytical work was supported by Rösch and Schmidbauer (2016), Varlik (2017), Torun and Demireli (2022), Çelik et al. (2023) and Çobanoğulları (2024) studies. A summary of the methodology, along with the variables used, is presented in Figure 1.

The first section employs Window Network Data DEA to evaluate the efficiency of aircraft manufacturers, with the model implemented using GAMS 48 software. Subsequently, in the second section, the relationship between operational and marketing efficiency scores (derived from Window Network DEA) and Environmental, Social, and Governance (ESG) combined scores is examined using Wavelet coherence analysis implemented in R programming environment, utilizing the WaveletComp package.

4. Results and Discussion

The results of the two-stage Window Network DEA analysis, illustrating the operational and market efficiency scores of aircraft manufacturers, are presented in Figures 2 and 3, with detailed efficiency scores provided in the Appendix I to V.

The initial analysis focused on the manufacturers' operational efficiency over a 20-year period. The operational efficiency scores revealed a hierarchical order with Embraer leading (0.973), followed by Airbus (0.946), Boeing (0.902), and Bombardier (0.868). However, market efficiency scores demonstrated a different pattern, with Boeing achieving the highest score (0.723), followed by Embraer (0.643), Airbus (0.460), and Bombardier (0.192).

As noted by Woo et al. (2021), Embraer's dual performance in both operational and market efficiency is particularly noteworthy, considering the market's dominance by Boeing and Airbus. A significant finding relates to Bombardier's strategic shift toward lower-capacity regional jet production post-2020, which yielded contrasting effects: enhancing operational efficiency while adversely impacting market efficiency.

These findings align with the operational and market efficiency differentials observed in two-stage Network DEA studies of airlines utilizing these manufacturers' aircraft. Both manufacturing and airline sectors demonstrated vulnerability to external shocks, particularly during financial crisis and pandemic periods. A notable pattern emerged wherein operational efficiency maintained relative stability while market efficiency experienced substantial decline.

The analysis suggests that during periods of economic shock, firms successfully maintained operational continuity by implementing cost optimization strategies before reaching their shutdown point (where average variable costs meet revenue). This strategic approach enabled operational sustainability despite compressed profit margins.

Figures 2 and Figure 3 show different patterns of efficiency across manufacturers. There are notable differences between the operational and market dimensions, which provide important insights into industry dynamics. These findings on aircraft manufacturers' operational and market efficiency provide important insights into competitive dynamics and strategic positioning in the industry. Embraer's strong performance in both operational efficiency (0.973) and market efficiency (0.643) is particularly noteworthy in a market dominated by Boeing and Airbus. This may be due to Embraer's focused strategy in the regional jet market and its effective use of economies of scale.

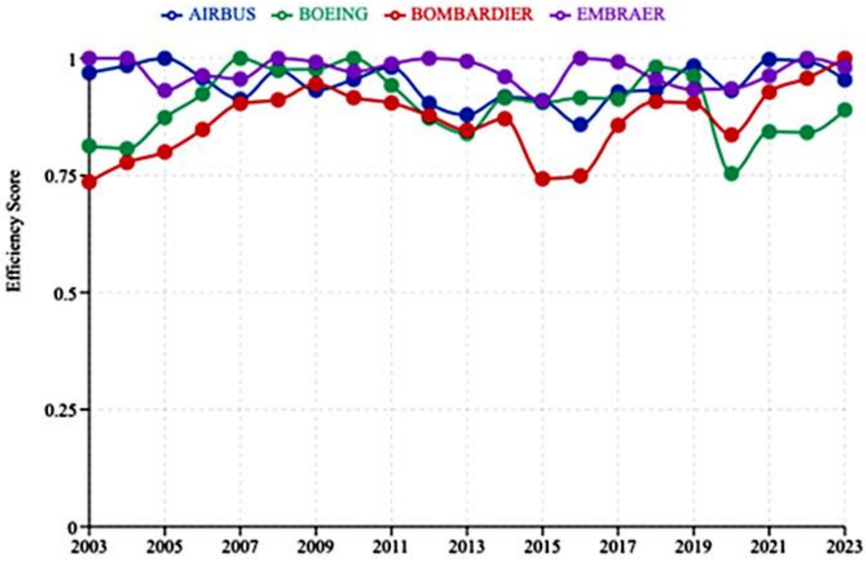

Figure 2 Operating Efficiency of Aircraft Manufacturers

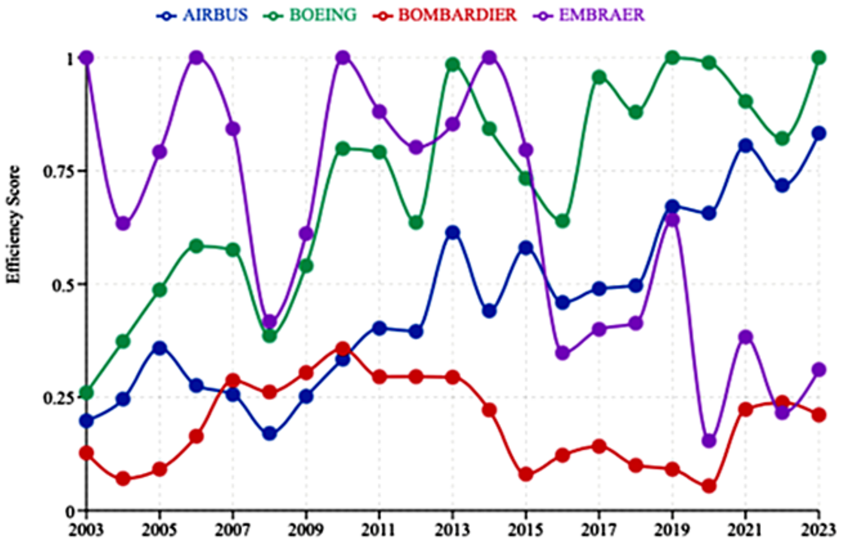

Figure 3 Marketing Efficiency of Aircraft Manufacturers

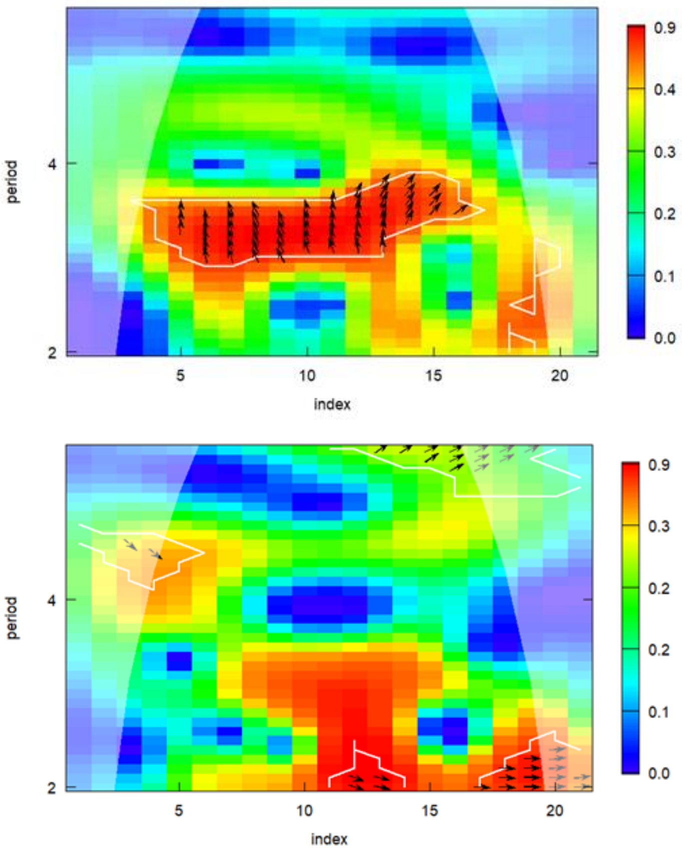

Figure 4 Airbus Operating Efficiency – ESG Combined Score / Marketing Efficiency – ESG Combined Score

Boeing's leading position in market efficiency (0.723) reflects its strong brand equity, global market reach and successful investor relations management. Airbus' high performance in operational efficiency (0.946) reflects the company's optimization of production processes and efficiency in resource management, while its relatively low performance in market efficiency (0.460) reflects the difficulty of market strategies in translating operational success into financial value.

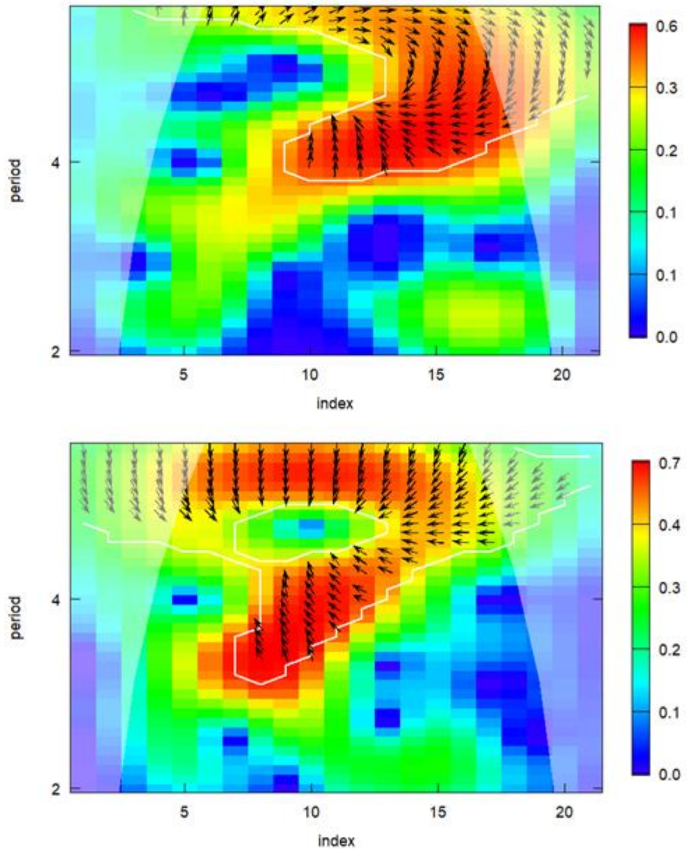

Figure 5 Boeing Operating Efficiency – ESG Combined Score / Marketing Efficiency – ESG Combined Score

Bombardier's strategic shift towards the production of lower capacity regional jets after 2020 improved its operational efficiency (0.868 with an upward trend) but had a negative impact on its market efficiency (lowest at 0.192). This suggests that focusing on niche markets may provide operational benefits but may create challenges in terms of market value.

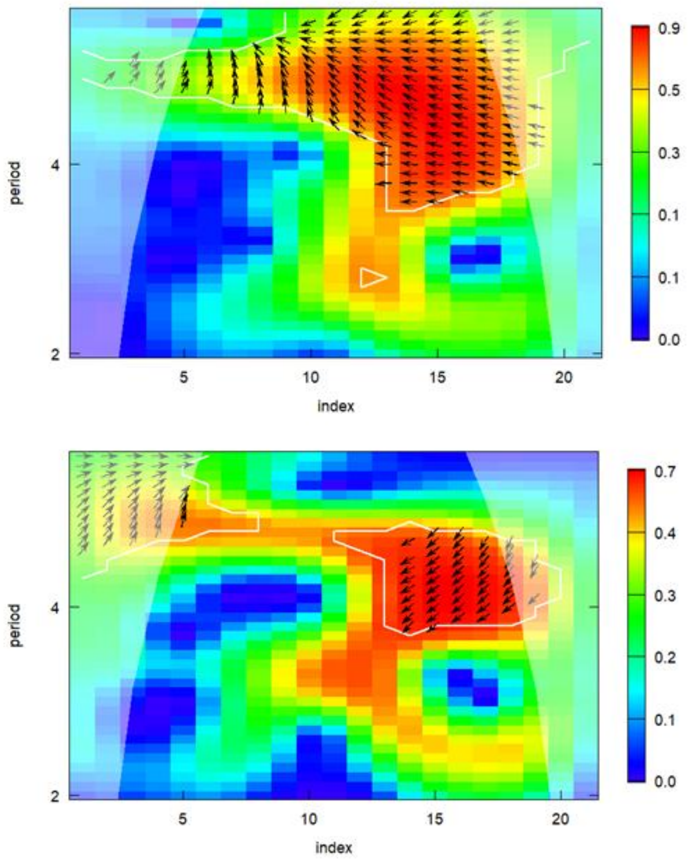

Figure 6 Bombardier Operating Efficiency – ESG Combined Score / Marketing Efficiency – ESG Combined Score

A notable finding is that for all manufacturers, operational efficiency remained relatively stable during the financial crisis and pandemic periods, while market efficiency declined significantly. This suggests that during periods of economic shocks, companies may be able to ensure operational sustainability by implementing cost optimization strategies before reaching the break-even point where average variable costs cover revenues, but the contraction of profit margins affects their market value.

In the second part of the analysis, the relationship between operational and market efficiency scores and ESG combined scores was examined using Wavelet coherence analysis. The manufacturer-specific findings reveal distinctive patterns of correlation between efficiency metrics and ESG performance. The color scale in Figure X represents the coherence values, with warmer colors (red) indicating a higher coherence (stronger correlation) and cooler colors (blue) indicating a lower coherence (weaker correlation). The results of the wavelet analysis reveal both temporal and structural features of the relationship between ESG performance and efficiency measures. This analysis is important as it shows how the impact of ESG integration differs in the short term (2-4 years) and in the long term (10-15 years).

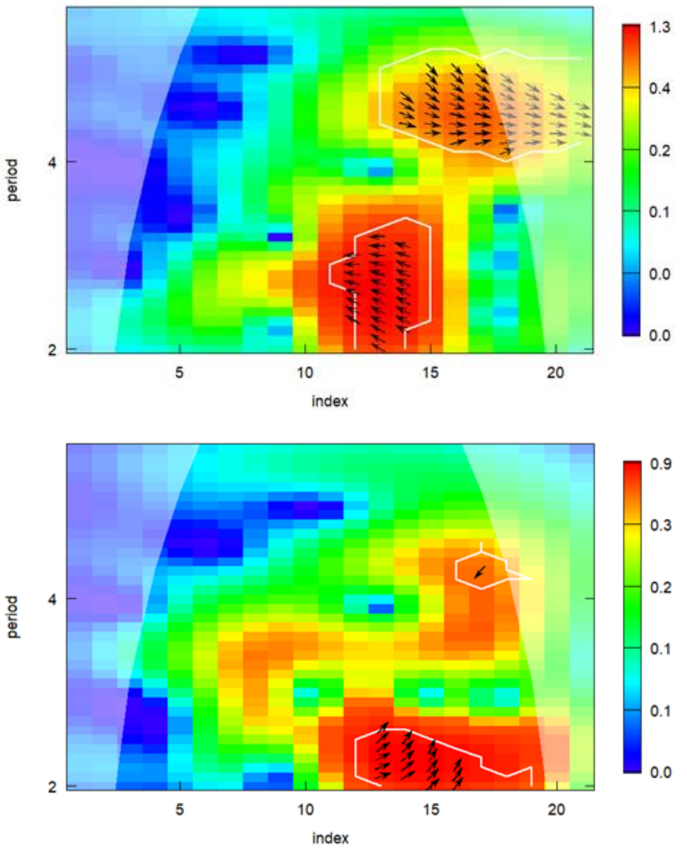

Figure 7 Embraer Operating Efficiency – ESG Combined Score / Marketing Efficiency – ESG Combined Score

The analysis of Airbus demonstrates a robust correlation (0.7-0.9 coherence) between operational efficiency and ESG performance, particularly evident in 3–4-year cycles in Figure 4. The persistence of this relationship throughout the 5–15-year timeframe suggests a structural rather than transitory connection. Regarding marketing efficiency, the analysis identified a strong correlation (0.9 coherence) during the 10–15-year interval, specifically within 2–3-year periods. However, the presence of low correlation values (0.0-0.3 coherence) in other periods indicates temporal variability in this relationship, suggesting that the marketing efficiency-ESG performance link is subject to cyclical fluctuations.

Boeing's analysis reveals different patterns, with operational efficiency and ESG performance showing a moderate correlation (0.3-0.5 coherence) in the 10–15-year range and 4-year period, indicating a lower level of integration compared to Airbus in Figure 5. However, the marketing efficiency analysis demonstrates a notably stronger correlation (0.4-0.7 coherence) in the 8–15-year range and 3-4-year period, suggesting that Boeing's ESG performance is more effectively integrated with its marketing strategies than its operational processes.

Bombardier's results demonstrate the highest sector-wide correlation (0.5-0.9 coherence) between operational efficiency and ESG performance, particularly evident in the 10–15-year range and 4-year period in Figure 6. The marketing efficiency analysis shows a moderate correlation (0.4-0.7 coherence) in the 12–15-year range. Notably, the low correlation values (0.0-0.1 coherence) in the early period data indicate a progressive strengthening of ESG integration over time, suggesting an evolving strategic approach to sustainability performance.

Embraer's results exhibit a unique dual-correlation pattern in operational efficiency within the 12–15-year range, characterized by a remarkably high correlation (1.0-1.3 coherence) in the 2–3-year period and a moderate correlation (0.4 coherence) in the 4-year period in Figure 7. The marketing efficiency analysis reveals a particularly strong correlation (0.9 coherence) in the more recent 15–20-year range, especially within 2-year cycles. This pattern suggests a recent and successful integration of ESG performance metrics into Embraer's marketing strategies, indicating an evolution in the company's approach to sustainability management.

The strong correlation between Airbus' operational efficiency and ESG performance (0.7-0.9 coherence) suggests that the company has successfully integrated sustainability initiatives into its operational processes. This relationship, particularly observed in 3-4 year cycles, indicates that Airbus' environmental initiatives, such as emissions reduction, energy efficiency and waste management, are translating into operational cost benefits. The strong correlation in marketing efficiency (0.9 coherence) is evident in the 10–15-year range, suggesting that the impact of ESG investments on market value occurs over the longer term. Boeing's moderate correlation between operational efficiency and ESG performance (0.3-0.5 coherence) suggests that the company has experienced some challenges in integrating sustainability initiatives into operational processes. In contrast, the stronger correlation in marketing efficiency (0.4-0.7 coherence) suggests that Boeing integrates ESG performance into marketing strategies more effectively than into operational processes. This may reflect the company's success in sustainability communication and investor relations. Bombardier's correlation between operational efficiency and ESG performance is the highest in the industry (0.5-0.9 coherence), suggesting that the company's sustainability-focused operational transformation has been effective. The low correlation values in the early data (0.0-0.1 coherence) suggest that ESG integration has strengthened over time and the strategic approach has evolved. Embraer's results show a unique pattern of dual correlation in operational efficiency, with an exceptionally high correlation in 2–3-year cycles (1.0-1.3 coherence) and a moderate correlation in 4-year cycles (0.4 coherence). This demonstrates the rapid integration of the company's short-term sustainability initiatives into operational processes. The analysis of marketing efficiency shows a particularly strong correlation (0.9 coherence) in the more recent 15–20-year range, suggesting that Embraer has successfully integrated ESG performance metrics into its marketing strategies.

The findings of this study, which examines the relationship between ESG performance and operational and market efficiency in the airline industry, show important parallels with the existing literature and offer new theoretical insights. When compared with Fang-Chen Kao et al. (2022) airline industry findings, similar patterns emerge, particularly with respect to the long-term relationship between operational efficiency and ESG performance. The current study adds a new analytical dimension to the literature by revealing the temporal dynamics of this relationship using wavelet coherence analysis. The strong correlation between Airbus' operational efficiency and ESG performance (0.7-0.9 coherence) confirms the findings of Bin Wang et al. (2025). However, the observed periodic fluctuations in marketing efficiency suggest that ESG integration is heterogeneously manifested in different operational processes, which points to an underexplored area in existing research. Boeing's results align with Ji et al. (2023) technical efficiency framework. Notably, the strong correlation in marketing efficiency (0.4-0.7 coherence) confirms Lujie Chen (2015) observations regarding the integration of ESG performance with market-oriented strategies. Bombardier and Embraer show patterns consistent with Qiang Cao et al. (2024) and Buallay (2019) in the banking sector. Bombardier's strong operational efficiency correlation (0.5-0.9 coherence) and Embraer's robust marketing efficiency relationship (0.9 coherence) suggest that organizational scale and market segmentation may act as important moderating variables in the ESG-efficiency relationship. This study goes beyond previous research in the literature by demonstrating both the temporal and structural nature of the effects of ESG performance on efficiency. This research also makes a methodological contribution by using a combination of Window Network DEA and wavelet analysis to capture both the efficiency measurement and the time-varying relationships, an approach that has not been used in the aviation sustainability literature to date. In particular, the strong correlations observed over 10–15-year periods suggest that ESG integration requires a long-term strategic approach beyond the short-term focus common in the literature. This finding provides an important theoretical contribution to sustainability research.

5. Conclusions

This study analyzes 20 years of performance of listed aircraft manufacturers and examines the impact of ESG performance on their operational and market efficiency. The research makes important theoretical, methodological and managerial contributions. The study measures the performance of a limited number of aircraft manufacturers in the marketplace through the use of Window Network DEA analysis. Wavelet coherence analysis was used to examine the relationship between efficiency scores and ESG combined scores, which include environmental, social and governance components. Wavelet coherence analysis provides statistical robustness through its ability to distinguish between unit root processes and short-run stationary processes in the spectral properties.

From a theoretical perspective, the study makes an important contribution to the literature by shedding light on the time dimension of the impact of ESG performance on efficiency. The strong correlations observed over 10–15-year periods suggest that ESG integration requires a long-term strategic approach beyond the short-term focus common in the existing literature. This finding highlights the need to extend sustainability research in terms of time horizons and strategic impact assessment. The time dimension identified in this study suggests that ESG rating systems in the aviation sector should adopt longer time horizons to capture the full impact of sustainability initiatives.

Methodologically, the application of wavelet coherence analysis allowed the dynamic nature of the ESG-efficiency relationship to be explored. This approach goes beyond the static analysis methods prevalent in the literature and provides insights into understanding the temporal evolution of the ESG-efficiency relationship. The framework developed here could be applied to other oligopolistic industries to investigate similar ESG-efficiency relationships.

From a managerial perspective, the results suggest that the impact of ESG integration on both operational and marketing efficiency exhibits firm-specific variation, and this heterogeneity suggests that ESG strategies need to be tailored to individual firm characteristics and operational contexts. Specific recommendations for aircraft manufacturers may include: Develop long-term (10-15 years) strategic planning frameworks for ESG integration to enable sustainable value creation beyond short-term performance indicators; Recognizing that environmental (E) initiatives mostly affect operational efficiency, while governance (G) factors tend to affect market efficiency, so strategic focus on ESG components should be aligned with business priorities; recognizing that market segmentation and company size are important moderating variables in the impact of ESG integration, with smaller and niche manufacturers (such as Embraer and Bombardier) needing to tailor sustainability initiatives to specific market segments; and understanding that during periods of economic shocks (financial crises, pandemics) the relationship between ESG performance and operational efficiency tends to be stronger, suggesting that sustainability-driven management can contribute to crisis resilience. Future research opportunities include investigating the discrete effects of ESG (environmental, social and governance) performance subcomponents on efficiency metrics. In addition, examining the impact of global disruptive events, such as the COVID-19 pandemic, on this relationship could provide valuable insights. These lines of research would improve our understanding of the relationship between ESG performance and firm efficiency and contribute to the development of more effective sectoral policies.

Nomenclature

CORSIA	: Carbon Offsetting and Reduction Scheme for International Aviation
DEA	: Data Envelopment Analysis
DMU	: Decision-Making Unit
ESG	: Environmental, Social, and Governance
GAMS	: General Algebraic Modelling System
ICAO	: International Civil Aviation Organization
IJAST	: International Journal of Aviation Science and Technology
SDGs	: Sustainable Development Goals
UN PRI	: United Nations Principles for Responsible Investment
δ	: Time parameter in wavelet analysis
ε	: Small positive value (non-Archimedean epsilon)
ν_i	: Weight assigned to input i
υ_r	: Weight assigned to output r
$\phi(t)$	: Mother wavelet function
$\phi^*(t)$	: Complex conjugate of wavelet function

E_k : Efficiency score of the kth Decision-Making Unit
E_k^(1.Stage) : First-stage (operational) efficiency
E_k^(2.Stage) : Second-stage (market) efficiency
i : Input index ($i = 1,\dots,m$)
j : Decision-Making Unit index ($j = 1,\dots,n$)
m : Total number of inputs
n : Total number of Decision-Making Units
p : Intermediate output/input index ($p = 1,\dots,t$)
r : Output index ($r = 1,\dots,s$)
S : Scale parameter in wavelet analysis
s : Total number of outputs
t : Total number of Intermediate outputs/inputs
W_p : Weight assigned to intermediate output/input p
$W_x(\delta, S)$: Wavelet transform of series x
$W_{xy}(\delta, S)$: Cross-wavelet transform
X_{ik} : Value of input i for the kth DMU
Y_{rk} : Value of output r for the kth DMU
Z_{pk} : Value of intermediate output/input p for the kth DMU
Angle(δ ,S) : Phase angle in wavelet analysis
Coherency(δ , S): Coherence measure in wavelet analysis (0-1 scale)
Power(δ , S) : Power spectrum in wavelet analysis
arg() : Argument function (phase angle)
max : Maximization operator
$\int$: Integration operator
$\sum$: Summation operator

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Appendix I Airbus Operating Efficiency and Marketing Efficiency Scores (2003-2023)

AIRBUS Operating Efficiency	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
W1	0,969	0,994	1,000																		
W2		0,975	1,000	0,923																	
W3			1,000	0,974	0,907																
W4				0,977	0,909	0,969															
W5					0,922	0,983	0,913														
W6						0,973	0,903	0,930													
W7							0,979	1,000	0,999												
W8								0,934	0,943	0,932											
W9									1,000	0,913	0,893										
W10										0,867	0,864	0,872									
W11											0,881	0,888	0,889								
W12												0,993	0,997	0,922							
W13													0,844	0,818	1,000						
W14														0,836	0,870	0,899					
W15															0,915	0,947	0,974				
W16																0,952	0,977	0,944			
W17																	1,000	0,922	1,000		
W18																		0,927	1,000	0,995	
W19																			0,993	0,991	0,954
Average	**0,969**	**0,985**	**1,000**	**0,958**	**0,913**	**0,975**	**0,932**	**0,955**	**0,981**	**0,904**	**0,879**	**0,918**	**0,910**	**0,859**	**0,928**	**0,933**	**0,984**	**0,931**	**0,998**	**0,993**	**0,954**

AIRBUS Marketing Efficiency	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
W1	0,198	0,213	0,297																		
W2		0,279	0,389	0,276																	
W3			0,389	0,276	0,232																
W4				0,276	0,232	0,116															
W5					0,304	0,152	0,180														
W6						0,243	0,288	0,334													
W7							0,288	0,334	0,433												
W8								0,334	0,433	0,464											
W9									0,341	0,365	0,623										
W10										0,357	0,609	0,441									
W11											0,609	0,441	0,624								
W12												0,441	0,624	0,602							
W13													0,492	0,388	0,512						
W14														0,388	0,512	0,544					
W15															0,445	0,473	0,671				
W16																0,473	0,671	0,653			
W17																	0,671	0,653	0,784		
W18																		0,664	0,797	0,701	
W19																			0,836	0,735	0,833
Average	**0,198**	**0,246**	**0,358**	**0,276**	**0,256**	**0,170**	**0,252**	**0,334**	**0,402**	**0,395**	**0,614**	**0,441**	**0,580**	**0,459**	**0,490**	**0,497**	**0,671**	**0,657**	**0,806**	**0,718**	**0,833**

Appendix II Boeing Operating Efficiency and Marketing Efficiency Scores (2003-2023)

BOEING Operating Efficiency	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
W1	0,813	0,832	0,857																		
W2		0,782	0,805	0,798																	
W3			0,958	0,987	1,000																
W4				0,987	1,000	0,975															
W5					1,000	0,975	0,972														
W6						0,977	0,972	1,000													
W7							0,986	1,000	0,991												
W8								1,000	0,991	0,957											
W9									0,845	0,787	0,772										
W10										0,873	0,865	0,865									
W11											0,881	0,881	0,870								
W12												1,000	0,991	0,997							
W13													0,855	0,861	0,813						
W14														0,889	0,936	0,944					
W15															0,991	1,000	0,957				
W16																1,000	0,957	0,762			
W17																	0,972	0,754	0,855		
W18																		0,746	0,838	0,840	
W19																			0,837	0,843	0,890
Average	**0,813**	**0,807**	**0,873**	**0,924**	**1,000**	**0,976**	**0,977**	**1,000**	**0,942**	**0,872**	**0,839**	**0,915**	**0,905**	**0,916**	**0,913**	**0,981**	**0,962**	**0,754**	**0,843**	**0,842**	**0,890**

BOEING Marketing Efficiency	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
W1	0,260	0,323	0,403																	
W2		0,424	0,529	0,584																
W3			0,529	0,584	0,522															
W4				0,584	0,522	0,263														
W5					0,683	0,344	0,385													
W6						0,551	0,618	0,799												
W7							0,618	0,799	0,852											
W8								0,799	0,852	0,747										
W9									0,670	0,587	1,000									
W10										0,574	0,977	0,843								
W11											0,977	0,843	0,832							
W12												0,843	0,832	0,838						
W13													0,536	0,540	1,000					
W14														0,540	1,000	0,963				
W15															0,870	0,838	1,000			
W16																0,838	1,000	0,983		
W17																	1,000	0,983	0,879	
W18																		1,000	0,894	0,802
W19																			0,937	0,841
Average	**0,260**	**0,374**	**0,487**	**0,584**	**0,576**	**0,386**	**0,540**	**0,799**	**0,791**	**0,636**	**0,985**	**0,843**	**0,733**	**0,639**	**0,957**	**0,880**	**1,000**	**0,989**	**0,903**	**0,822**

Appendix III Bombardier Operating Efficiency and Marketing Efficiency Scores (2003-2023)

BOMBARDIER Operating Efficiency	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
W1	0,736	0,796	0,782																		
W2		0,759	0,738	0,746																	
W3			0,880	0,899	0,904																
W4				0,899	0,904	0,911															
W5					0,903	0,913	0,951														
W6						0,910	0,952	0,928													
W7							0,933	0,908	0,977												
W8								0,912	0,937	0,919											
W9									0,800	0,853	0,844										
W10										0,860	0,840	0,829									
W11											0,856	0,845	0,828								
W12												0,939	0,931	0,924							
W13													0,469	0,482	0,813						
W14														0,841	0,856	0,875					
W15															0,902	0,922	0,889				
W16																0,926	0,892	0,883			
W17																	0,930	0,753	0,942		
W18																		0,874	0,921	0,955	
W19																			0,920	0,960	1,000
Average	**0,736**	**0,778**	**0,800**	**0,848**	**0,904**	**0,911**	**0,945**	**0,916**	**0,905**	**0,877**	**0,847**	**0,871**	**0,743**	**0,749**	**0,857**	**0,908**	**0,904**	**0,837**	**0,928**	**0,958**	**1,000**

BOMBARDIER Marketing Efficiency	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
W1	0,127	0,061	0,076																		
W2		0,080	0,099	0,164																	
W3			0,099	0,164	0,260																
W4				0,164	0,260	0,178															
W5					0,341	0,233	0,217														
W6						0,374	0,348	0,357													
W7							0,348	0,357	0,318												
W8								0,357	0,318	0,347											
W9									0,250	0,273	0,299										
W10										0,267	0,292	0,222									
W11											0,292	0,222	0,091								
W12												0,222	0,091	0,160							
W13													0,059	0,103	0,148						
W14														0,103	0,148	0,109					
W15															0,129	0,095	0,091				
W16																0,095	0,091	0,054			
W17																	0,091	0,054	0,217		
W18																		0,055	0,221	0,233	
W19																			0,232	0,244	0,211
Average	**0,127**	**0,071**	**0,091**	**0,164**	**0,287**	**0,262**	**0,304**	**0,357**	**0,295**	**0,296**	**0,294**	**0,222**	**0,080**	**0,122**	**0,142**	**0,100**	**0,091**	**0,054**	**0,223**	**0,239**	**0,211**

Appendix IV Embraer Operating Efficiency and Marketing Efficiency Scores (2003-2023)

EMBRAER Operating Efficiency	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
W1	1.000	1,000	0,905																		
W2		1,000	0,922	0,943																	
W3			0,967	0,972	0,954																
W4				0,974	0,956	1,000															
W5					0,957	1,000	1,000														
W6						1,000	0,998	1,000													
W7							0,977	0,979	1,000												
W8								0,935	0,973	1,000											
W9									0,991	1,000	1,000										
W10										1,000	0,981	0,942									
W11											1,000	0,960	0,953								
W12												0,980	0,947	1,000							
W13													0,825	1,000	1,000						
W14														1,000	0,977	0,930					
W15															1,000	0,951	0,973				
W16																0,983	1,000	0,948			
W17																	0,827	0,958	1,000		
W18																		0,899	0,944	1,000	
W19																			0,944	1,000	0,981
Average	**1,000**	**1,000**	**0,931**	**0,963**	**0,956**	**1,000**	**0,992**	**0,971**	**0,988**	**1,000**	**0,994**	**0,961**	**0,908**	**1,000**	**0,992**	**0,955**	**0,933**	**0,935**	**0,963**	**1,000**	**0,981**

EMBRAER Marketing Efficiency	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
W1	1,000	0,549	0,656																		
W2		0,719	0,860	1,000																	
W3			0,860	1,000	0,764																
W4				1,000	0,764	0,284															
W5					1,000	0,372	0,436														
W6						0,596	0,699	1,000													
W7							0,699	1,000	0,948												
W8								1,000	0,948	0,941											
W9									0,746	0,741	0,866										
W10										0,724	0,847	1,000									
W11											0,847	1,000	0,903								
W12												1,000	0,903	0,456							
W13													0,582	0,294	0,418						
W14														0,294	0,418	0,453					
W15															0,364	0,394	0,642				
W16																0,394	0,642	0,153			
W17																	0,642	0,153	0,373		
W18																		0,156	0,379	0,211	
W19																			0,397	0,221	0,311
Average	**1,000**	**0,634**	**0,792**	**1,000**	**0,843**	**0,417**	**0,611**	**1,000**	**0,881**	**0,802**	**0,853**	**1,000**	**0,796**	**0,348**	**0,400**	**0,414**	**0,642**	**0,154**	**0,383**	**0,216**	**0,311**

Appendix V ESG Combined Scores for Aircraft Manufacturers (2003-2023)

ESG Combined Scores	AIRBUS	BOEING	BOMBARDIER*	EMBRAER*
2003	34,95	64,08	38,92	44,74
2004	38,85	57,31	39,74	45,25
2005	49,18	60,76	12,24	45,76
2006	50,67	40,08	19,87	46,27
2007	40,59	26,17	35,34	46,78
2008	46,81	37,96	57,07	47,28
2009	66,97	34,27	65,05	44,30
2010	61,10	52,67	68,19	56,24
2011	66,57	69,42	47,14	39,21
2012	74,99	50,38	43,16	65,70
2013	75,31	34,97	51,34	45,98
2014	70,27	42,29	45,43	40,22
2015	78,35	52,03	70,60	68,73
2016	46,62	68,23	72,73	35,65
2017	39,44	55,14	41,17	63,61
2018	43,99	47,37	42,52	44,72
2019	50,95	41,09	40,90	42,50
2020	42,97	44,31	57,37	39,72
2021	55,17	45,66	43,35	60,65
2022	45,28	40,09	43,30	68,13
2023	56,40	45,36	55,45	54,91

*For missing data points, ESG scores were estimated using the Double Exponential Smoothing Method in Minitab 17. This approach was applied to Bombardier's scores for 2003-2004 and Embraer's scores for 2003-2008

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Research Article

A Performance Measurement Study Using the CRITIC and ARAS Methods in the International Aerospace Industry

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Abstract

This study aims to evaluate the performance of manufacturing companies operating in the international aerospace industry. In this context, the financial performance of 12 leading companies from 2019-2023 is analysed through multi-criteria decision-making processes using the CRITIC and ARAS methods. In order to evaluate the performance of the companies in question, a number of financial indicators are taken into consideration, including total capital, capital expenditures, gross income, operating expenses, total liabilities and working capital. The CRITIC method was employed to ascertain the relative importance of the criteria, while the ARAS method was utilised to evaluate the performance of the companies in question. The results demonstrate that the Transdigm Group is the most successful company, with General Electric consistently ranking second. Conversely, the performance of companies such as Airbus and Boeing has exhibited variability over time. The findings of this study offer valuable insights for strategic performance evaluation in the aerospace industry.

Keywords

CRITIC
ARAS
MCDM
Aerospace Industry
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Time Scale of Article

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1. Introduction

The aerospace sector exerts a considerable influence on the natural environment, the global economy and society at large (ATAG, 2014). The sector has experienced exponential growth in recent years as a consequence of urbanization. It is anticipated that demand for passenger travel will increase by five per cent per year over the next two decades, resulting in a projected requirement for 56,000 additional aircraft by 2040 (ICAO, 2013). The sector contributes approximately $664 billion to the global economy on an annual basis, with an estimated contribution of $1 trillion to the global GDP by 2026. A significant number of individuals are employed by major aircraft manufacturing companies, with Boeing alone employing over 150,000 people (Boeing, 2024).

The aerospace industry is widely acknowledged as one of the most value-added industrial sectors in any economy (Hausmann et al., 2011). A significant number of countries worldwide have pursued the development of a domestic aerospace industry as a component of their national industrial development strategies. Examples of countries that have sought to develop an aerospace industry include Argentina in the late 1920s, Indonesia in the 1970s and, more recently, Portugal, the United Arab Emirates and several developing regions in Asia, which have been pursuing this goal since the beginning of this century. The motivations of governments seeking to create a national aerospace industry include enhancing international prestige, increasing military self-sufficiency and promoting economic development (Eriksson, 2023). Policy makers have focused on aircraft production with the rationale that the production of an entire aircraft can trigger the establishment of

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component and system suppliers in the vicinity, stimulating job creation, capacity building and economic growth (Niosi and Zhegu, 2005).

The aircraft industry comprises a multitude of stakeholders, including original equipment manufacturers (OEMs) such as aircraft and component manufacturers. Prominent examples of OEMs in the industry include Boeing, Airbus, General Electric (GE) Aerospace, Lockheed Martin, BAE Systems, and Rolls-Royce Holdings. The entities that provide maintenance, repair and overhaul (MRO) services are referred to as MROs. The customer base is comprised of commercial airline operators and the military. Additionally, aircraft and component manufacturers frequently function as service providers, offering maintenance packages to airline operators with the objective of generating post-sales revenue. It is not uncommon for airline operators to integrate with MRO organizations, while OEMs frequently offer customers the option of customization (Singamneni et al., 2019).

This sector makes significant contributions in areas such as technological innovations, large-scale projects and defense systems, and stands out as a strategic industry in which the largest companies operate worldwide (Bharadwaj et al., 2015). The financial performance of companies is critical for their competitiveness and sustainability in the sector (Kılıçlı and Aygün, 2023). Therefore, it is necessary to evaluate the performance of companies operating in the aerospace industry by considering the above factors. In this context, various methods have been developed to evaluate the performance of companies operating in this field (Vermeulen and Van Tooren, 2006; Noll, 2015; Hsieh et al., 2020), but it is seen that the application of multi-criteria decision making (MCDM) methods is limited among these methods.

The objective of this study is to analyze the financial performance of leading manufacturing companies in the international aerospace industry using MCDM methods. The study employs the CRITIC and ARAS methods to evaluate the performance of 12 companies operating within the aerospace industry. Financial indicators, including total capital, capital expenditures, gross income, operating expenses, total liabilities, and working capital, are employed as performance criteria. The combination of these methods provides a more comprehensive analysis of the financial health and overall performance of the companies in question.

The continuation of the research is designed as follows: Firstly, an overview of the research conducted in the field of aviation using MCDM methods will be presented. The following section will present the methodology employed in the research, including an explanation of the MCDM methods utilized and the dataset. Subsequently, the research findings will be presented, and the study will conclude with a discussion of the conclusions and recommendations.

2. Literature Review

In the field of air transportation, research has been conducted in a number of areas, including the financial and operational performance measurement of airline companies, the performance evaluation of airports, the evaluation of airline and airport service quality, and the selection of personnel and aircraft using multi-criteria decision-making methods. Table 1 represents a summary of the aforementioned research.

Ömürbek and Kınay (2013) employed the TOPSIS method to evaluate the financial performance of two airlines operating in Turkey and Germany. The results indicated that the Turkish airline exhibited superior performance compared to its German counterpart. In a similar vein, Altın et al. (2017) employed the ENTROPY-based COPRAS and Grey Relational Analysis (GRA) methods to evaluate Europe's largest airports. Their findings revealed that the three airports with the highest performance ratings were the main airports in Madrid, Frankfurt and Paris, respectively. In a further study, Bakır and Alptekin (2018) used the CODAS method to evaluate the performance of airline companies in terms of both airport services and cabin services. The objective of Raj and Srivastava (2018) was to develop a composite index (CI) for the evaluation of the sustainability performance of an aircraft manufacturing company, employing the Fuzzy Best Worst Multi-Criteria (FBWM) decision-making approach. The findings of the study indicated that economic considerations represent the most influential aspect of sustainability within the aerospace industry. Bakır and Atalık (2018) applied the ENTROPY-based ARAS method to evaluate the quality of airline services. The findings of the study indicate that the Japanese flag carrier All Nippon Airways provides the optimal level of service quality. In a further study, Ilgaz Yıldırım et al. (2019) employed the ARAS method to evaluate the criteria used in the selection of airline personnel. The findings of the research indicated that sectoral competence is the most crucial criterion for support staff. Kiracı and Bakır (2019) used the CRITIC-based EDAS method to evaluate the operational performance of airline businesses. Their findings revealed that these businesses were negatively affected by the global economic crisis of 2008. Öztürk and Onurlubaş (2019) adopted subjective methods to weight airline service quality criteria and employed the TOPSIS method to rank airline businesses. In their study, Çetin and Altan (2019) evaluated airline performance using the Fuzzy TOPSIS method. The most significant criterion among the evaluated criteria was 'Large and New Aircraft'. The criterion with the lowest level of importance was 'Sales

Office/Agency Services'. In the ranking of airline companies, Turkish Airlines is identified as the best-performing company.

Dilmen and Çetinyokuş (2020) evaluated the feasibility of a multi-airport system in the context of Ankara province using the AHP-TOPSIS-ELECTRE method. A financial performance analysis of Pegasus and Turkish Airlines was conducted by Macit and Göçer (2020), employing the Grey Relational Analysis method. The findings of the research indicate that Pegasus exhibits superior financial performance in comparison to Turkish Airlines; however, Turkish Airlines displays a more favorable profitability ratio. In a similar vein, Altınkurt and Merdivenci (2020) conducted an evaluation of the service quality provided by airline companies that cater to business travelers, applying the AHP and EDAS method. The findings of the research indicate that airline companies with their origins in the Far East perform better. Özdağoğlu et al. (2020) performed an analysis of the performance of airline companies utilizing Isparta Süleyman Demirel Airport, undertaking this assessment employing the BWM, MAIRCA, and MABAC methods. In 2020, a hybrid multi-criteria decision-making model was proposed, based on the integration of PIPRECIA and MAIRCA methods, for the evaluation of the operational performance of airline companies operating in emerging markets. The study concluded that the most significant performance indicator is operating costs (Bakır et al., 2020). In a departure from the approaches taken by other studies in the literature, Kiracı and Akan (2020) utilized a hybrid methodology combining the Interval Type-2 Fuzzy Analytical Hierarchy Process (IT2FAHP) and the Interval Type-2 Fuzzy Technique (IT2FTOPSIS) for the purpose of aircraft selection. The findings indicate that the Airbus A321neo is the optimal commercial aircraft for airlines in technical, economic, and environmental terms.

Bae et al. (2021) aim to assess the competitiveness of airlines and evaluate their financial and operational performance according to these criteria. The researchers test a hybrid method that combines FAHP and TOPSIS methods. Özaslan et al. (2021) used AHP and TOPSIS methods in the selection of single-engine piston aircraft. Özbek and Ghouchi (2021) evaluated the financial performance of the leading European airlines using the WASPAS-based EDAS method. Keleş et al. (2021) evaluated the service quality of airports in terms of passengers using fuzzy CODAS and ARAS methods. Kurt and Kablan (2022) investigated the impact of Covid-19 on airline financial performance using TOPSIS-MABAC methods. Keleş (2022) analyzed the performance measurement of THY over the years using the CRITIC-based MABAC method. Gedik and Bayram (2022) analyzed the cabin service quality of airlines with ENTROPY-based ARAS. The results show that the best airlines are Norwegian, Easy Jet and Vueling.

Mercan and Can (2023) investigated the factors that are effective in the selection of employees in airline companies using the FUCOM method. The results show that technical competence is the most important selection criterion. Sarıgül et al. (2023) determined the service quality evaluation at airports with the MEREC-based hybrid MARCOS-CoCoSo method. Boz et al. (2023) performed the selection of air cargo operations using the Bayesian BWM-WASPAS method. The main criteria of economy and quality were identified as the most important criteria in the selection. Bakır and İnce (2024) used the LOPCOW-AROMAN model in airline passenger satisfaction. Tezcan (2024) proposed a model with AHP and TOPSIS methods integrated with Pythagorean fuzzy sets in aircraft type selection for airlines. The research results show that Airbus A350-1000 aircraft is the most ideal aircraft. Seker (2024) identified agile features for LCCs with integrated SWARA, MABAC, and Picture Fuzzy Sets method. Xie et al. (2024) evaluated airline service quality using text mining and the TOPSIS, VIKOR and AISM methods from the CRM methods.

3. Methodology

The research evaluated the performance of international aerospace manufacturing companies. In this context, CRITIC and ARAS, which are widely used MCDM methods in this field, were used in an integrated way. The CRITIC method was used to obtain the weights of the evaluation criteria, and the ARAS method was used to rank the companies.

The companies included in the study are among the world's leading organizations in the engineering, aerospace and aviation industries. These companies often focus on large-scale defense projects, commercial aircraft manufacturing, aerospace engines, space exploration and cyber security solutions. They also provide state-of-the-art infrastructure and solutions to commercial and military customers. Others manufacture only commercial aircraft, serving major airlines and producing cutting-edge technologies that are reshaping the commercial aviation industry.

MCDM uses a set of criteria selected to comprehensively assess the financial performance and overall well-being of the firm. The term 'total capital' refers to all the financial resources of the firm (Antonelli et al., 2023), while capital expenditure describes the significant expenditures made to develop or acquire long-term assets (Beranek et al., 1995).

Table 1. Studies Using MCDM Methods in Air Transportation

Author(s)	**MCDM Method**	**Scope**
Ömürbek and Kınay (2013)	TOPSIS	Airline financial performance
Altın et al. (2017)	ENTROPY-COPRAS-GRA	Airport performance measurement
Bakır and Alptekin (2018)	CODAS	Airline service quality
Raj and Srivastava (2018)	Fuzzy (BWM)	Aircraft manufacturing firms' performance measurement
Bakır and Atalık (2018)	ENTROPY-ARAS	Airline service quality
Ilgaz Yıldırım et al. (2019)	ARAS	Airline staff selection
Kiracı and Bakır (2019)	CRITIC-EDAS	Airline performance measurement
Öztürk and Onurlubaş (2019)	AHP-TOPSIS	Airline service quality
Çetin and Altan (2019)	Fuzzy TOPSIS	Airline performance evaluation
Dilmen and Çetinyokuş (2020)	AHP-TOPSIS-ELECTRE	Multi-airport system suitability
Macit and Göçer (2020)	GİA	Airline financial performance
Altınkurt and Merdivenci (2020)	AHP-EDAS	Airline service quality
Özdağoğlu et al. (2020)	BWM-MAIRCA-MABAC	Airline performance measurement
Bakır et al. (2020)	PIPRECIA-MAIRCA	Airline operational performance measurement
Kiracı and Akan (2020)	(IT2F) AHP-TOPSIS	Aircraft selection
Bae et al. (2021)	Fuzzy AHP-TOPSIS	Airline financial and operational performance measurement
Özaslan et al. (2021)	AHP-TOPSIS	Single-engine aircraft selection
Özbek and Ghouchi (2021)	WASPAS-EDAS	Airline financial performance
Keleş et al. (2021)	(Fuzzy) CODAS-ARAS	Airport service quality
Kurt and Kablan (2022)	TOPSIS-MABAC	Airline financial performance
Keleş (2022)	CRITIC-MABAC	Airline performance measurement
Gedik and Bayram (2022)	ENTROPY-ARAS	Airline cabin service quality
Mercan and Can (2023)	FUCOM	Airline labor selection
Sarıgül et al. (2023)	MEREC-MARCOS-CoCoSo	Airport service quality
Boz et al. (2023)	Bayesian BWM-WASPAS	Choosing an air cargo company
Bakır and İnce (2024)	LOPCOW-AROMAN	Airline passenger satisfaction
Tezcan (2024)	Pisagor Fuzzy Sets-AHP-TOPSIS	Aircraft type selection
Seker (2024)	SWARA-MABAC-PiFS	Agile attributes for LCC
Xie et al. (2024)	TOPSIS-VIKOR-AISM	Airline service quality
This study	CRITIC-ARAS	*Aerospace manufacturing firms' performance measurement*

The amount of money generated from sales after deducting direct costs is known as gross revenue, which indicates how profitable the company is (Abdel-Basset et al., 2020). Operating expenses are a measure of the operational efficiency of a company, as they represent the regular costs incurred to maintain its main activities (Khalid and Khan, 2017). Working capital is the difference between short-term assets and liabilities and indicates the ability of the business to finance its day-to-day operations (Baños-Caballero et al., 2010), while total liabilities cover the debts and obligations of the business to third parties (Rehwinkel, 2016). These parameters allow the analysis of many different financial scenarios, ranging from the growth capacity of the company to its debt position. Table 2 lists the research criteria and alternatives used.

Table 2. Criteria and Alternatives Used in the Study

Criteria			Alternatives	
Codes	**Direction**	**Criteria Name**	**Codes**	**Firms**
			A1	AIRBUS
C1	MAX	Total Capital	A2	BAE SYSTEMS
			A3	BOEING
C2	MIN	Capital Expenditures	A4	GENERAL DYNAMICS
			A5	GENERAL ELECTRIC
C3	MAX	Gross Income	A6	LOCKHEED MARTIN
			A7	NORTHROP GRUMMAN
C4	MIN	Operating Expenses	A8	ROLLS ROYCE
			A9	RTX CORPORATION
C5	MIN	Total Liabilities	A10	SAFRAN
			A11	THALES
C6	MAX	Working Capital	A12	TRANSDIGM GROUP

3.1 Weighting of Criteria: CRITIC Method

The Criteria Importance Through Intercriteria Correlation (CRITIC) method, as proposed by Diakoulaki et al., (1995), (Houqiang and Ling, 2012; Xie et al., 2014), is primarily used for the determination of the weight of the attributes. In the CRITIC method, the weighting process is performed by taking into account the standard deviation of the decision matrix for the evaluation criteria and the correlation coefficient of these criteria (Çakır and Perçin, 2013). This method is based on the premise that the features do not contradict one another, and the weights of the features are determined using the decision matrix. The CRITIC method has been applied in various fields, including automatic areal feature matching (Kim et al., 2011; Kim and Yu, 2015), medical quality assessment (Ping, 2014) and ranking of processing procedures (Madic and Radovanovic, 2015). The application stages of the CRITIC method are outlined below (Diakoulaki et al., 1995):

In the CRITIC method, the decision matrix must be prepared first. The decision matrix is given in equation 1.

$$Y = [y_{ij}] = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \qquad (1)$$

The decision matrix is normalized using the equation (Eq 2) and (Eq 3). The cost and benefit characteristics of the evaluation criteria are taken into account.

$$r_{ij} = \frac{y_{ij} - y_j^{min}}{y_j^{max} - y_j^{min}} \qquad (2)$$

$$r_{ij} = \frac{y_j^{max} - y_{ij}}{y_j^{max} - y_j^{min}} \qquad (3)$$

In order to show the direction and strength of the relationship between the evaluation criteria, a matrix R = $(\rho_{jk})_{mxm}$ consisting of linear correlation coefficients (ρ_{jk}) is created and the correlation coefficient of the relevant criteria is calculated using (Eq 4).

$$\rho_{jk} = \frac{\sum_{i=1}^{m}(r_{ij} - \bar{r}_j)(r_{ik} - \bar{r}_k)}{\sqrt{\sum_{i=1}^{m}(r_{ij} - \bar{r}_j)^2 \sum_{i=1}^{m}(r_{ik} - \bar{r}_k)^2}} \qquad (4)$$

(Eq 5) is used to determine the value σj, which indicates the standard deviation value of each evaluation criterion, and Cj, which expresses the amount of information for each evaluation criterion.

$$C_j = \sigma_j \sum_{k=1}^{n}(1 - \rho_{jk}) \qquad (5)$$

Finally, the weight value of each evaluation criterion is calculated using (Eq 6) and the criterion weights are obtained.

$$w_j = C_j / \sum_{k=1}^{n} C_k \qquad (6)$$

3.2 Ranking of Alternatives: ARAS Method

ARAS (Additive Ratio Assessment Method), one of the MCDM, was developed by Zavadskas and Turskis in 2010. According to Ilgaz Yıldırım et al., (2019), this method assigns the values of the selection alternatives with their ratios to the ideal decision alternative according to the utility function. A feature that distinguishes the ARAS method from the other MCDM techniques in the literature is that it compares the utility function values of the alternatives with the value of the alternative in the ideal scenario (Bakır and Atalık, 2018). The following steps constitute the ARAS technique (Zavadskas and Turskis, 2010):

First, the decision matrix is constructed as in (Eq 7):

$$X = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ X_{m1} & X_{m2} & \cdots & X_{mn} \end{bmatrix} ; i = 0,1, \ldots, m; \; j = 1,2, \ldots, n \qquad (7)$$

In this matrix there are m options and n evaluation criteria. If the reference value for the criteria is not known, the best value based on the benefit (maximum) or cost (minimum) characteristic is determined using (Eq 8):

$$\begin{cases} If \ \ maks_i x_{ij} \ ; x_{0j} = maks_i x_{ij} \\ If \ \ min_i x_{ij}^* \ \ ; x_{0j} = min_i x_{ij}^* \end{cases} \quad (8)$$

Obtaining the normalized decision matrix is the next step. The process of standardizing the criteria in the range of 0 to 1 is known as normalizing the criteria. During the normalization process, (Eq 9) and (Eq 10) are used to calculate the normalized values of the criteria that are desired to be maximum or minimum according to the problem objective.

$$or\ criteria\ that\ are\ required\ to\ take\ the\ maximum\ value: \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}} \quad (9)$$

$$for\ criteria\ that\ are\ required\ to\ take\ the\ minimum\ value: \frac{1/x_{ij}}{\sum_{i=0}^{m} 1/x\ _{ij}} \quad (10)$$

The next step is to obtain the weighted normalized decision matrix. The importance coefficients of the criteria are used to perform the weighting step following the normalization step. According to Zavadskas and Turskis (2010), the importance coefficients of the criteria must satisfy the condition 0 < w_j < 1. (Eq 11) provides the following formula to obtain the normalized weights:

$$x_{ij} = \bar{x}_{ij} w_j \qquad i = 0,1,\dots,m \quad (11)$$

The normalized value of criterion j is denoted by $\bar{x}_{ij}$ in the (Eq 11), where w_j is the importance coefficient of criterion j. In the next step, the optimality function (S_i) is calculated. In this step, the best values for each alternative are determined. Equation (12) is used to calculate the values of the alternatives.

$$S_i = \sum_{j=1}^{n} x_{ij} \ ; \qquad i = 0,1,\dots,m \quad (12)$$

The optimality function of the i-th alternative is denoted by S_i. Following this procedure, the S_i values of the alternatives are divided by the optimal value S_0 to determine the K_i utility ratings. Equation (13) is used to determine the K_i values.

$$K_i = \frac{S_i}{S_0} \ ; \qquad i = 0,1,\dots,m \quad (13)$$

The K_i values obtained are used to analyse the efficiency of the utility functions of the alternatives. This is equivalent to ranking the alternatives from best to worst and ranking the K_i values from largest to smallest (Zavadskas and Turskis, 2010). The K_i value is between 0 and 1. The relative utility efficiency of the alternatives is calculated using the K_i values obtained. These values are then ranked from largest to smallest and the selection alternatives are evaluated (Ilgaz Yıldırım et al., 2019).

4. Results

This part of the research provides information on the application stages of the CRITIC and ARAS methods. As part of the study, the performance indicators of 12 companies in the international aerospace manufacturing industry were analyzed for the period from 2019 to 2023. Six financial indicators were included in the research.

4.1 CRITIC Results

The initial step involved the implementation of the CRITIC method for the purpose of assigning weights to the performance indicators. In this study, the weighting process was carried out separately for each year of the 2019-2023 period, as the criteria weights used for each year were derived from the decision matrix. However, for the sake of exemplification and to conserve space, only the weighting process conducted on the data from 2023 is presented here.

In the initial phase of the CRITIC method, a decision matrix is constructed to represent the evaluation criteria. In this case, the decision matrix comprised 12 manufacturing enterprises operating in the aerospace industry (Alternative) and 6 criteria (Indicator), organized using (Eq 1). The resulting decision matrix for these enterprises is presented in Table 3. As shown in Table 3, firms A10 (Safran) and A11 (Thales) report negative working capital. This situation may initially appear as a data anomaly; however, it can also be interpreted as a characteristic of capital-intensive industries such as aerospace and defense. In such sectors, firms often have high short-term liabilities due to large-scale production contracts and advance payments, which may temporarily result in negative working capital without necessarily implying financial distress.

In the second stage of the CRITIC method, the decision matrix is normalized according to the benefit or cost nature of each criterion, as shown in (Eq 2). During this normalization process, the minimum and maximum values of each criterion are first identified. Then, the normalized values are calculated using (Eq 2), which adjusts each value based on the type of criterion (benefit or cost). Specifically, for benefit-type criteria, normalization is achieved by dividing each value by the sum of the values in its column, whereas for cost-type criteria, the inverse approach is used. The resulting normalized decision matrix is presented in Table 4.

In the subsequent phase of the CRITIC approach, the direction and intensity of the relationship between the performance measurement criteria were determined by applying a correlation analysis to the relevant criteria with the assistance of (Eq 3). Table 5 presents the findings of the correlation analysis conducted on the performance measurement criteria.

Table 3. Initial Decision Matrix (2023)

	MAX	MIN	MAX	MIN	MIN	MAX
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
A1	34837660	3363279	11072033	67441953	107692167	11323369
A2	20956378	1053687	8120788	26606232	26446776	1058790
A3	29875000	1527000	7724000	78615000	154181000	13448000
A4	30435000	904000	6672000	38027000	33483000	7183000
A5	48290000	1595000	17719000	63484000	123891000	8923000
A6	24126000	1691000	10071000	59012000	42668000	3584000
A7	28581000	1775000	6551000	36753000	30729000	1764000
A8	1685134	547254	4585962	18689548	41003218	4062945
A9	103800000	2415000	12089000	60173000	100424000	1656000
A10	18818267	907236	4783109	23135081	41071466	-1556522
A11	13988087	689632	5254255	18491640	33768818	-2830181
A12	17352000	139000	3721000	3630000	21948000	5159000

Table 4. Normalized Decision Matrix (2023)

	MAX	MIN	MAX	MIN	MIN	MAX
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
A1	0,325	0,000	0,525	0,149	0,352	0,869
A2	0,189	0,716	0,314	0,694	0,966	0,239
A3	0,276	0,570	0,286	0,000	0,000	1,000
A4	0,282	0,763	0,211	0,541	0,913	0,615
A5	0,456	0,548	1,000	0,202	0,229	0,722
A6	0,220	0,519	0,454	0,261	0,843	0,394
A7	0,263	0,493	0,202	0,558	0,934	0,282
A8	0,000	0,873	0,062	0,799	0,856	0,423
A9	1,000	0,294	0,598	0,246	0,407	0,276
A10	0,168	0,762	0,076	0,740	0,855	0,078
A11	0,120	0,829	0,110	0,802	0,911	0,000
A12	0,153	1,000	0,000	1,000	1,000	0,491
STD. DEV.	0,25145	0,27410	0,28595	0,31827	0,34267	0,30585

In the final phase of the CRITIC technique, the quantity of information and the weights assigned to the criteria are determined. In this context, the information amount (Cj) is initially determined through the application of (Eq 4). Subsequently, the value of (Cj) for each criterion is divided by the total value of (Cj) for all criteria. The resulting value is then expressed as the criterion weight value, which is calculated with the help of Equation (5). Table 6 presents the (Cj) and (Wj) values for the performance measurement criteria.

Up to this point in the analysis, only the criterion weight value and the amount of information value for 2023 have been determined. The criteria weight values for the 2019-2023 period are presented in Table 7.

Table 7 illustrates that the weight values attributed to the criteria of aerospace manufacturing firms included in the study for the 2019-2023 period fall within the range of 0.133-0.209. The rankings of the criteria weights vary from year to year. Consequently, when the evaluation is made on the basis of the 2023 period, it is evident that the variable with the lowest weight on the performance of aerospace manufacturing firms is Capital Expenditures (C2), while the variable with the highest weight is Working Capital (C6). The weight change graph of the criteria weights for different years is provided in Figure 1 for reference.

Table 5. Correlation Matrix (2023)

Alternatives	C1	C2	C3	C4	C5	C6
C1	1,000	-0,584	0,629	-0,540	-0,501	0,095
C2	-0,584	1,000	-0,632	0,783	0,592	-0,389
C3	0,629	-0,632	1,000	-0,731	-0,650	0,394
C4	-0,540	0,783	-0,731	1,000	0,854	-0,656
C5	-0,501	0,592	-0,650	0,854	1,000	-0,712
C6	0,095	-0,389	0,394	-0,656	-0,712	1,000

Table 6. Amount of Information and Criterion Weight Value (2023)

	C1	C2	C3	C4	C5	C6
Rjj	5,901	5,230	5,991	5,290	5,418	6,267
Cj	1,484	1,434	1,713	1,684	1,857	1,917
Wj	0,147	0,142	0,170	0,167	0,184	0,190

Table 7. Weight of criteria (2019-2023)

Alternatives	C1	C2	C3	C4	C5	C6
2019	0,175	0,157	0,173	0,178	0,172	0,145
2020	0,186	0,145	0,133	0,156	0,171	0,209
2021	0,151	0,155	0,163	0,175	0,195	0,160
2022	0,148	0,158	0,165	0,178	0,187	0,164
2023	0,147	0,142	0,170	0,167	0,184	0,190

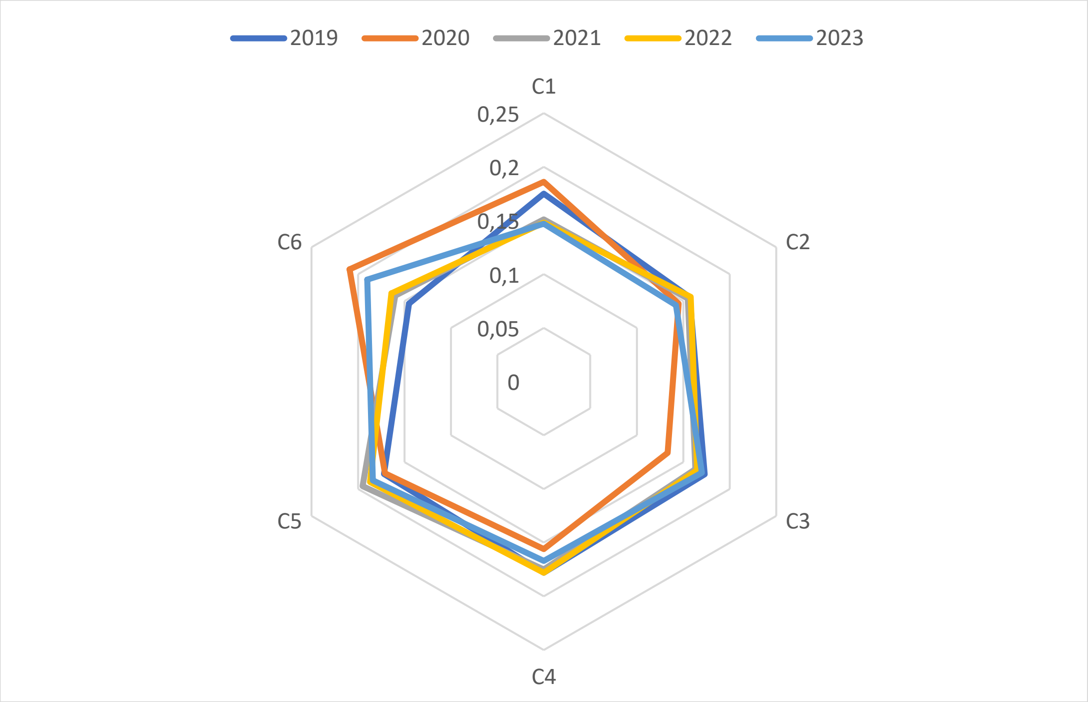

Fig. 1. Weight Level Change of Performance Criteria by Years (2019-2023)

Table 8. Initial Decision Matrix for ARAS (2023)

	MAX	MIN	MAX	MIN	MIN	MAX
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
A1	34837660	3363279	11072033	67441953	107692167	11323369
A2	20956378	1053687	8120788	26606232	26446776	1058790
A3	29875000	1527000	7724000	78615000	154181000	13448000
A4	30435000	904000	6672000	38027000	33483000	7183000
A5	48290000	1595000	17719000	63484000	123891000	8923000
A6	24126000	1691000	10071000	59012000	42668000	3584000
A7	28581000	1775000	6551000	36753000	30729000	1764000
A8	1685134	547254	4585962	18689548	41003218	4062945
A9	103800000	2415000	12089000	60173000	100424000	1656000
A10	18818267	907236	4783109	23135081	41071466	-1556522
A11	13988087	689632	5254255	18491640	33768818	-2830181
A12	17352000	139000	3721000	3630000	21948000	5159000

Table 9. Transformed Decision Matrix for ARAS (2023)

	MAX	MIN	MAX	MIN	MIN	MAX
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Wj	0,1471	0,1421	0,1698	0,1669	0,1840	0,1900
A_0 (Optimum)	103800000	7,194E-06	17719000	2,755E-07	4,556E-08	13448000
A1	34837660	2,973E-07	11072033	1,483E-08	9,286E-09	11323369
A2	20956378	9,49E-07	8120788	3,759E-08	3,781E-08	1058790
A3	29875000	6,549E-07	7724000	1,272E-08	6,486E-09	13448000
A4	30435000	1,106E-06	6672000	2,63E-08	2,987E-08	7183000
A5	48290000	6,27E-07	17719000	1,575E-08	8,072E-09	8923000
A6	24126000	5,914E-07	10071000	1,695E-08	2,344E-08	3584000
A7	28581000	5,634E-07	6551000	2,721E-08	3,254E-08	1764000
A8	1685134	1,827E-06	4585962	5,351E-08	2,439E-08	4062945
A9	103800000	4,141E-07	12089000	1,662E-08	9,958E-09	1656000
A10	18818267	1,102E-06	4783109	4,322E-08	2,435E-08	-1556522
A11	13988087	1,45E-06	5254255	5,408E-08	2,961E-08	-2830181
A12	17352000	7,194E-06	3721000	2,755E-07	4,556E-08	5159000
TOTAL	476544526	2,39713E-05	116082147	8,69728E-07	3,26932E-07	67223401

4.2 ARAS Results

In this section, the decision matrix employed in the Entropy method calculations is utilized to rank the alternatives by evaluating the performance of aerospace manufacturing firms in accordance with the ARAS method. In this context, the initial decision matrix is presented in Table 8.

Moreover, the ARAS approach is structured in a way that makes (Eq 7) the optimal means of generating the criterion values, which are then represented in the decision matrix. The values in each column of the matrix in Table 9 are selected with the objective of obtaining the optimal values A_0 based on the cost or benefit attribute. In the ARAS method, an additional artificial alternative, referred to as A_0 (optimum), is introduced to serve as the ideal solution against which all other alternatives are compared. A_0 represents the best achievable values across all criteria, allowing the relative utility of each real alternative to be measured. In this study, A_0 was generated based on the maximum or minimum values for each criterion, depending on whether the criterion is benefit-type or cost-type.

The normalized decision matrix is presented in Table 10 for reference. In order to transform the selection matrix into standardized values, (Eq 8) and (Eq 9) are employed to normalize it subsequent to the addition of optimal values to the data set. (Eq 8) is employed for criteria C1, C3 and C6, while (Eq 9) is utilized for the remaining criteria.

The weight coefficients, which represent the relative importance of the alternatives, are multiplied by the scores of the alternatives in the ARAS technique. At this stage, Table 10 is used for the weighting process, and (Eq 10) is used to determine the Entropy weight values. For example, the Entropy weight for criterion C1 is multiplied by each column element in Table 10 to obtain weighted values. Table 11 shows the selection matrix produced after weighting.

Table 10. Normalized Decision Matrix for ARAS (2023)

	MAX	MIN	MAX	MIN	MIN	MAX
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Wj	0,1471	0,1421	0,1698	0,1669	0,1840	0,1900
A_0 (Optimum)	0,2178	0,3001	0,1526	0,3167	0,1393	0,2000
A1	0,0731	0,0124	0,0953	0,0170	0,0284	0,1684
A2	0,0439	0,0395	0,0699	0,0432	0,1156	0,0157
A3	0,0626	0,0273	0,0665	0,0146	0,0198	0,2000
A4	0,0638	0,0461	0,0574	0,0302	0,0913	0,1068
A5	0,1013	0,0261	0,1526	0,0181	0,0246	0,1327
A6	0,0506	0,0246	0,0867	0,0194	0,0716	0,0533
A7	0,0599	0,0235	0,0564	0,0312	0,0995	0,0262
A8	0,0035	0,0762	0,0395	0,0615	0,0745	0,0604
A9	0,2178	0,0172	0,1041	0,0191	0,0304	0,0246
A10	0,0394	0,0459	0,0412	0,0496	0,0744	-0,0231
A11	0,0293	0,0604	0,0452	0,0621	0,0905	-0,0421
A12	0,0364	0,3001	0,0320	0,3167	0,1393	0,0767

Table 11. Weighted Normalized Matrix for ARAS (2023)

	MAX	MIN	MAX	MIN	MIN	MAX
Alternatives	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Wj	0,1471	0,1421	0,1698	0,1669	0,1840	0,1900
A_0 (Optimum)	0,0320	0,0427	0,0259	0,0529	0,0256	0,0380
A1	0,0108	0,0018	0,0162	0,0028	0,0052	0,0320
A2	0,0065	0,0056	0,0119	0,0072	0,0213	0,0030
A3	0,0092	0,0039	0,0113	0,0024	0,0037	0,0380
A4	0,0094	0,0066	0,0098	0,0050	0,0168	0,0203
A5	0,0149	0,0037	0,0259	0,0030	0,0045	0,0252
A6	0,0074	0,0035	0,0147	0,0033	0,0132	0,0101
A7	0,0088	0,0033	0,0096	0,0052	0,0183	0,0050
A8	0,0005	0,0108	0,0067	0,0103	0,0137	0,0115

A9	0,0320	0,0025	0,0177	0,0032	0,0056	0,0047
A10	0,0058	0,0065	0,0070	0,0083	0,0137	-0,0044
A11	0,0043	0,0086	0,0077	0,0104	0,0167	-0,0080
A12	0,0054	0,0427	0,0054	0,0529	0,0256	0,0146

Table 12. The Optimality Function (2019-2023)

	2019		**2020**		**2021**		2022		2023	
Alternatives	S_i	K_i	S_i	K_i	S_i	K_i	S_i	K_i	S_i	K_i
A_0 (Optimum)	0,2762	1,000	0,2357	1,000	0,2286	1,000	0,2290	1,000	0,2171	1,000
A1	0,0211	0,077	0,0445	0,189	0,0499	0,219	0,0565	0,247	0,0688	0,317
A2	0,0537	0,195	0,0497	0,211	0,0538	0,236	0,0565	0,247	0,0555	0,255
A3	0,0364	0,132	0,0699	0,296	0,0672	0,294	0,0668	0,291	0,0685	0,316
A4	0,0468	0,169	0,0509	0,216	0,0546	0,239	0,0560	0,244	0,0679	0,313
A5	0,1456	0,527	0,1209	0,513	0,0831	0,364	0,0801	0,350	0,0773	0,356
A6	0,0412	0,149	0,0469	0,199	0,0520	0,228	0,0522	0,228	0,0523	0,241
A7	0,0451	0,163	0,0520	0,221	0,0506	0,222	0,0489	0,213	0,0503	0,232
A8	0,0304	0,110	0,0309	0,131	0,0451	0,197	0,0476	0,208	0,0535	0,247
A9	0,0725	0,262	0,0726	0,308	0,0712	0,311	0,0702	0,306	0,0657	0,302
A10	0,0382	0,138	0,0435	0,185	0,0488	0,214	0,0406	0,177	0,0369	0,170
A11	0,0430	0,156	0,0475	0,202	0,0509	0,223	0,0517	0,226	0,0396	0,183
A12	0,1498	0,542	0,1350	0,573	0,1440	0,630	0,1441	0,629	0,1465	0,675

Table 13. Ranking of the Firms (2019-2023)

Alternatives	**2019**	**2020**	**2021**	**2022**	**2023**
AIRBUS	12	10	10	5	3
BAE SYSTEMS	4	7	6	6	7
BOEING	10	4	4	4	4
GENERAL DYNAMICS	5	6	5	7	5
GENERAL ELECTRIC	2	2	2	2	2
LOCKHEED MARTIN	8	9	7	8	9
NORTHROP GRUMMAN	6	5	9	10	10
ROLLS ROYCE	11	12	12	11	8
RTX CORPORATION	3	3	3	3	6
SAFRAN	9	11	11	12	12
THALES	7	8	8	9	11
TRANSDIGM GROUP	1	1	1	1	1

Once the weighted normalized decision matrix had been obtained, the values of the optimality function for each choice were generated. At this juncture, (Eq 11) and (Eq 12) were employed to derive the utility degrees K_i and S_i, respectively. Table 12 presents the optimality functional values for the 2019-2023 time period.

The equation S_i/S_0 was employed to calculate the K_i values obtained in the preceding step. The S_i value employed in this step is derived from the data obtained in the preceding step, whereas the S_0 value represents the fixed S_i value of option A_0. Ultimately, the alternatives are evaluated according to their performance, with the ranking of the K_i utility degrees from largest to smallest serving as a basis for this assessment. Table 13 illustrates the rankings of the enterprises for the 2019-2023 period, as determined by the application of the ARAS method.

The TransDigm Group has demonstrated superior performance and stability relative to other companies, consistently occupying the top position (rank 1) over the past five years. Furthermore, General Electric has attained a robust and resilient standing, ranking second for a period of five years. This suggests the existence of a stable financial position or competitive advantages in the market. Airbus has demonstrated a noteworthy advancement, ascending from the 12th position in 2019 to the 3rd position in 2023. This upward trajectory may be attributed to strategic alterations or operational enhancements that have augmented the company's performance. BAE Systems and General Dynamics demonstrate a moderate degree of consistency, occupying positions between fourth and seventh over the course of the observation period. While these companies continue to perform in a consistent manner, they are not exceptional performers, exhibiting neither significant progress nor decline.

Boeing commenced 2019 in tenth position but has since maintained a consistent performance, occupying fourth place from 2020 to 2023. Boeing's ranking suggests that the company will recover and demonstrate resilience in the coming years, despite the challenges it has faced, including those resulting from the 737 MAX crisis. The fluctuating rankings of Lockheed Martin, Northrop Grumman, Rolls-Royce and Thales, which are typically situated in the lower echelons of the table, suggest a lack of consistency in performance or the ability to sustain a trajectory of steady growth. Safran's consistent ranking between 9th and 12th places demonstrates that, despite facing certain challenges in comparison to other companies in the sector, it has not declined significantly over time. Between 2019 and 2022, RTX Corporation (formerly Raytheon) retained its third position; however, it declined to sixth place in 2023. This may be indicative of an underlying issue or shift in the company's strategic direction.

5. Discussion and Conclusion

The principal aim of this study is to evaluate the performance of aerospace companies through the application of multi-criteria decision-making techniques utilizing a range of financial indicators. In this context, the performance of 12 aerospace companies over the period 2019-2023 is analyzed. The CRITIC method was employed to ascertain the significance and weighting of the criteria to be utilized in the study, while the ARAS method was used to rank the firms according to their performance. In the context of this study, a number of financial variables were employed as performance indicators for the enterprises in question. These included total capital, working capital, gross income, capital expenditures, operating expenses and total liabilities.

The application of the CRITIC method resulted in differing weights for the criteria on an annual basis. In the 2023 period, the most significant evaluation criterion is working capital (0.190), followed by total liabilities (0.184), gross revenue (0.170), operating expenses (0.167), total capital (0.147), and capital expenditures (0.142). In the 2021-2022 period, the criterion with the highest weight value was total liabilities, while the criterion with the lowest weight value was total capital. In the 2020 assessment, working capital was identified as the criterion with the highest weight, while gross income was identified as the criterion with the lowest weight. In 2019, operating expenses were identified as the criterion with the highest weight, while working capital was identified as the criterion with the lowest weight.

The results of the performance evaluation conducted using the ARAS method, subsequent to the CRITIC method, indicate that Transdigm Group is the most effective enterprise across all years, with General Electric ranking second. In the 2023 period, Airbus was ranked third and Boeing was ranked fourth. In the selected period, it was observed that the performance rankings of some enterprises exhibited fluctuations from year to year, while others demonstrated a relatively stable outlook.

Specifically, the strong and consistent performance of TransDigm Group and General Electric can be explained by their favorable values across the most influential indicators — particularly working capital and total liabilities, which had the highest weights in 2023 according to the CRITIC method (0.190 and 0.184, respectively). TransDigm consistently demonstrates robust working capital levels, indicating efficient short-term financial management and liquidity. At the same time, it maintains relatively low liabilities, improving its overall financial risk profile. These two criteria alone accounted for nearly 38% of the total weight in 2023, significantly boosting the firm's final performance score under the ARAS method. Similarly, General Electric's strong results stem from a combination of high gross income and solid working capital, which aligns with the next most significant criteria weights (gross income: 0.170; total capital: 0.147). This suggests strong operational efficiency and revenue generation capacity. These firms outperformed their peers not necessarily because they had the best values in every criterion, but because they consistently performed well across those criteria deemed most important in each year — a fact captured dynamically by the CRITIC weighting system.

This clarification helps better interpret the performance results and the strategic advantages of the top-performing firms.

The findings of this study have important strategic implications for stakeholders in the aerospace industry. Given the prominence of working capital and total liabilities in performance evaluation, firms should prioritize liquidity management and debt optimization to strengthen their financial standing. Moreover, consistent performers like TransDigm and GE provide benchmarks for best practices in financial planning, investment control, and capital efficiency. For investors and managers, this study highlights the critical indicators that most significantly influence firm performance in this capital-intensive and technologically demanding sector.

The findings of this study provide important insights into the financial performance dynamics of the aerospace manufacturing sector and contribute to the growing body of literature on multi-criteria decision-making (MCDM) applications in industrial performance assessment. The results confirm that certain financial indicators—particularly working capital and total liabilities—carry significant weight in performance evaluation, as also emphasized by Baños-Caballero et al. (2010) and Rehwinkel (2016), who highlighted the relevance of liquidity and debt management for sustainable firm performance.

The consistent top-ranking of TransDigm Group across all five years reveals a strong and stable financial structure. This performance is supported by the company's ability to manage short-term assets effectively and minimize excessive liabilities, aligning with Antonelli et al. (2023), who emphasized that optimized capital utilization enhances firm value and long-term competitiveness. Similarly, General Electric maintained a second-place position throughout the period, reflecting robust gross income and operational efficiency, in line with findings by Abdel-Basset et al. (2020) and Khalid & Khan (2017), who noted that high revenue generation combined with controlled operating costs is a key determinant of superior financial outcomes.

In contrast, companies like Rolls-Royce, Safran, and Thales exhibited more volatile or consistently lower rankings, which may reflect strategic challenges, suboptimal capital expenditures, or liquidity pressures. The variability observed in Airbus and Boeing's rankings across the years is noteworthy. While Boeing recovered to a higher ranking after a downturn—potentially reflecting post-crisis stabilization—Airbus showed a marked improvement by 2023, which could be linked to operational reforms or post-pandemic recovery strategies. These trends underscore the sector's sensitivity to external shocks, such as the COVID-19 crisis, as also discussed by Kurt and Kablan (2022).

From a methodological perspective, the integration of CRITIC and ARAS proved to be effective in capturing both the objective importance of criteria and the relative performance of firms. This aligns with prior studies such as Kiracı and Bakır (2019) and Bakır et al. (2020), who demonstrated the value of hybrid MCDM models in handling multidimensional financial data and generating actionable rankings for managerial decision-making. Objective weighting methods like CRITIC offer distinct advantages over purely subjective approaches by capturing both the variability and interdependence among criteria, leading to more robust and data-driven evaluations. This reinforces the notion suggested by Diakoulaki et al. (1995) that objective MCDM tools can improve transparency and reliability in performance assessment models.

The study was conducted with the objective of evaluating the performance of firms engaged in manufacturing activities within the aviation and aerospace industry. In the course of this evaluation, a number of limitations were encountered. Firstly, although the study was designed to be conducted on the 20 largest aerospace and defense industry companies globally, the necessary data could not be obtained, resulting in the study being evaluated on 12 existing enterprises. Furthermore, the narrow scope of the study, encompassing only six evaluation criteria, represents another limitation.

In future studies, it would be beneficial to diversify the weighting and ranking methods employed in order to facilitate a more nuanced comparison of the findings. In this context, weighting can be performed with methods such as LOPCOW and ENTROPY, while ranking can be performed with methods such as TOPSIS, VIKOR, EDAS, WASPAS and CODAS. Furthermore, the integration of fuzzy methods enables the revelation of situations in uncertain environments. In addition to the objective methods enumerated above, the evaluation of performance can be informed by the incorporation of subjective criteria. In this context, methods such as AHP, BWM and SWARA can be employed for this purpose, with the results subjected to comparative analysis.

CRediT Author Statement

Mehmet Yaşar: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Writing- Reviewing and Editing.

Nomenclature

CRITIC : Criteria Importance Through

Intercriteria Correlation

ARAS : Additive Ratio Assessment

MCDM : Multi Criteria Decision Making

ATAG : Air Transport Research Group

GDP : Gross Domestic Product

GE : General Electric

OEM : Original Equipment Manufacturer

MRO : Maintenance, Repair and Overhaul

TOPSIS : Technique for Order Preference by Similarity to Ideal Solution

COPRAS : Complex Proportional Assessment

GRA : Grey Relational Analysis

FBWM : Fuzzy Best–Worst Method

EDAS : Evaluation based on Distance from Average Solution

AHP : Analytic Hierarchy Process

ELECTRE : Elimination and Choice Expressing Reality

BWM : Best–Worst Method

MAIRCA : Multi-Attributive Ideal-Real Comparative Analysis

MABAC : Multi-Attributive Border Approximation Area Comparison

PIPRECA : Pivot Pairwise Relative Criteria Importance Assessment

IT2F : Interval Type-2 Fuzzy

WASPAS : Weighted Aggregated Sum Product Assessment

CODAS : Combinative Distance-based Assessment

THY : Türk Hava Yolları

FUCOM : Full Consistency Method

CoCoSo : Combined Compromise Solution

LOPCOW : Logarithmic Percentage Change-Driven Objective Weighting

AROMAN : Alternative Ranking Order Method Accounting for Two-Step Normalization

SWARA : Stepwise Weight Assessment Ratio Analysis

VIKOR : VlseKriterijumska Optimizacija I Kompromisno Resenje

AISM : Adversarial Interpretive Structural Model

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