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Why was the four-engine passenger aircraft discontinued? What engine improvements have been made since, and what challenges remain?

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Abstract. The Boeing 747 and Airbus A380 passenger jets used to control long-distance traveling, a symbol of safety, distance, and status. However, advances in high-bypass turbofan engines, rising fuel prices, and growing environmental pressures have made this configuration increasingly uneconomic. This project investigates three questions: why four-engine airliners have been discontinued, and what engine improvements have enabled twin-engine aircraft to replace them while still leaving essential challenges for the future. Drawing on technical textbooks, academic articles, industry reports, and historical case studies, the dissertation explains the working principles of turbofan engines, traces the development of quadjets, and compares the performance, fuel efficiency, maintenance demands, and regulatory constraints of four- and two-engine layouts. The analysis shows that modern twin-engine wide-bodies can match or exceed the range and payload of classic quadjets with much lower fuel burn and maintenance cost, especially after the relaxation of Extended-range Twin-engine Operational Performance Standards (ETOPS) rules and the shift towards point-to-point networks. At the same time, gas-turbine technology is approaching limits in bypass ratio, temperature, and materials, while climate policy highlights unresolved CO_2 and non-CO_2 impacts. Future propulsion concepts such as open-rotor engines, hybrid-electric systems, and sustainable aviation fuels offer potential benefits but introduce new technical and economic trade-offs.

Keywords: four-engine passenger aircraft, twin-engine aircraft, turbofan engine, high-bypass ratio

1. Introduction

Commercial air travel is now routine, linking people and businesses across continents in hours. For much of the jet age, the largest and most familiar airliners—notably the Boeing 747 and Airbus A380—used four engines, and these "quadjets" became icons of safety, range, and prestige, reflecting the limited thrust and reliability of early jet engines. Over the last two decades, however, this technological and commercial context has shifted. Advances in high-bypass turbofan engines mean that a pair of large engines can now deliver more thrust, much higher fuel efficiency, and greater reliability than four smaller engines on earlier designs. At the same time, airlines face intense pressure to cut costs and address climate change, as long-haul flights contribute disproportionately to global aviation emissions. Comparative fuel-efficiency studies show that four-engine wide-bodies are typically less efficient per passenger than modern twin-engine types on similar routes, leaving airlines with higher fuel bills and a larger environmental footprint. Regulatory changes, such as the progressive relaxation of ETOPS rules, have also enabled highly reliable twin-engine aircraft to fly routes once reserved for four-engine designs. As a result, production of primary four-engine passenger aircraft has stopped, fleets are being retired early, and commentators now describe a gradual "fade" of the four-engine airliner.

Against this background, the central problem for this dissertation is threefold. First, why have four-engine passenger aircraft, which once dominated long-haul travel, become commercially unviable? Second, what specific improvements in jet-engine technology have enabled twin-engine aircraft to replace them? Third, what technical and environmental challenges remain for future passenger aircraft? Many individual sources discuss aspects of these questions—such as the history of jet engines, fuel-efficiency rankings, or new propulsion concepts—but few bring them together in a single, accessible analysis for a non-specialist reader.

This project aims to fill that gap by combining technical explanations with economic and regulatory perspectives, so that the reasons for the disappearance of four-engine airliners can be understood coherently. To achieve this aim, the literature review is organised into four sections. Section 2.1 introduces the working principles of modern aircraft and turbofan engines. Section 2.2 traces the development of four-engine passenger aircraft from the early jet age to the Boeing 747 and Airbus A380. Section 2.3 examines advances in engine technology and compares the performance of four- and two-engine layouts.

In contrast, Section 2.4 considers economic and legislative factors such as maintenance costs, airline business models, and ETOPS regulations. The discussion chapter then synthesises these findings, identifying the key reasons for the discontinuation of four-engine passenger aircraft and evaluating the main challenges and potential future improvements in passenger aircraft propulsion. In this way, the project develops a clear line of argument that directly answers the research question and prepares the ground for a well-reasoned conclusion, in line with the Extended Project marking criteria.

2. Research review

Designing and building aircraft represents one of the highest achievements of modern engineering. This section provides an overview of information about the plane, including its working principle and the history of the four-engine aircraft. Moreover, it compares the performance of four-engine aviation with that of contemporary two-engine planes and considers other factors.

2.1. Working principles of aircraft

When identifying the causes of discontinuation, understanding the fundamental working principles of aircraft is critical. The working principle of an aeroplane is fundamentally based on generating lift through its wings to overcome its weight, and thrust through its engines to overcome drag. The core function of the engine is to create thrust, not only to overcome the drag caused by air friction and vortices, but also to provide the power required for the aircraft to change its flight state, such as accelerating or climbing. Most jet-propelled aircraft use a turbofan design. The turbofan can be thought of as a high-tech propeller inside a duct called a diffuser, driven by a gas generator [1]. In the book, *Jet Propulsion* [2], the specific functions of each engine component are described (see Figure 1).

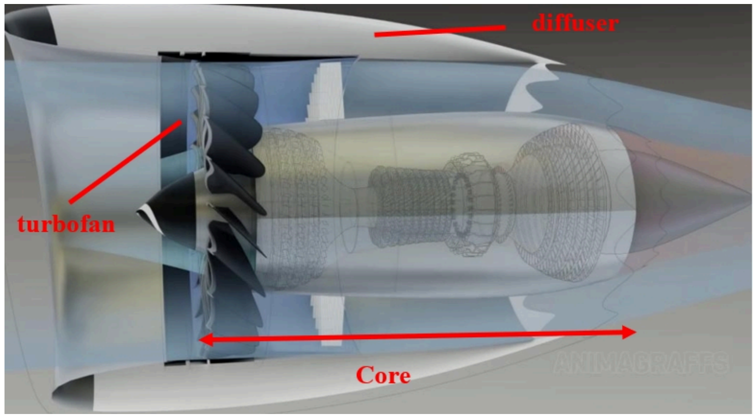

Figure 1. 3D illustration of Turbofan 4 [3]

Core: The core of a jet engine is a gas generator that creates high-pressure gas to power a turbine. This setup has a compressor, a combustor, and a turbine section.

1. Compressor: Compressed air enables a much more powerful combustion reaction, relative to engine size. Compression occurs in stages, forcing incoming air into an increasingly narrow chamber. A single compressor stage consists of a spinning rotor paired with a ring of stationary stator vanes attached to the core casing. As the rotor blades force air through the compressor, the stator slows the swirling momentum in exchange for increased air pressure.

2. Combustor: Air is mixed with fuel and ignited as it passes through the combustor, producing a high-velocity jet of superheated gas. Then, compressed air enters the inlet nozzles, each of which is coupled with a fuel injector and designed to swirl the incoming fuel and air for an even mix. A couple of ignitor plugs, not unlike the spark plugs found in car engines, ignite this mixture, and the reaction spreads evenly around the ring. Once started, combustion continues as long as air and fuel are supplied.

3. Turbine: Turbines at the rear of the jet engines are powered by exhaust gases exiting the combustor. A significant portion of the power is used to operate the fan, while the compressor stages consume a smaller share. Turbine fins become extremely hot; therefore, some of the compressor air is diverted for cooling, and special coatings are used to keep temperatures down (see Figure 2).

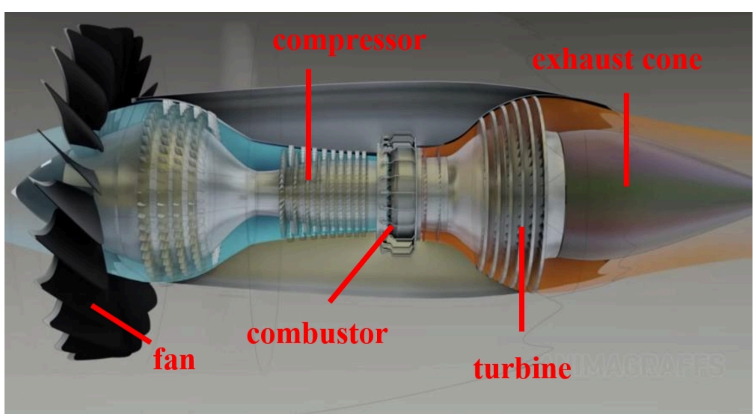

Figure 2. 3D illustration of the Core 4 [3]

Exhaust Cone: The exhaust cone is specially shaped to mix and accelerate exhaust streams. It also covers sensitive internal engine parts.

Fan: Early jet engines were turbojets, where all incoming air flows through the core. Most modern winged aircraft engines are turbofans, in which only a fraction of the air enters the core, or gas generator, and the resulting power turns a specially designed fan. Again, the fan can be thought of as a high-tech propeller inside a duct. Air that does not enter the core is called bypass air [2].

High-bypass engines are designed to move large quantities of air at slow cruising speeds, in the range of 310 to 620 mph [1]. The trade-off for high efficiency is engine size—high-bypass engines can be huge, with massive fans relative to their core size. Commercial airliners and military transport aircraft are examples of such applications. Moreover, Exhaust velocity is a significant factor in jet engine noise. High-bypass engines surround the fast-moving core exhaust with large amounts of slower-moving bypass air, resulting in quieter operation.

Actually, the propulsion systems that enable aircraft flight, rather than the airframe itself, are what matter. However, it establishes the critical link between airframe and propulsion system performance. The evaluation of aircraft is characterized by a continuous trend toward stronger, lighter materials (from wood to all-metal structures to composites) and significantly improved aerodynamic quality. Specifically, a key metric for aerodynamic efficiency is the Lift-to-Drag ratio (L/D). In the book, Elements of Propulsion: Gas Turbines and Rockets [1], it records the historical progression of L/D, form around 5 for early gliders to nearly 20 for late 1940s subsonic transports (like the B707) and further improvements for supersonic aircraft (like the Concorde) through innovations, like swept-back wings and the area rule [1].

2.2. Development history of the four-engine aircraft

Four-engine aircraft, also known as "quadjets", have played a crucial role in the history of commercial aviation. From the early years of the jet age to the heyday of wide-body airliners, quadjets were not only the very icons of technological progress but also essential aerial links to the world. Section 2.2 describes the entire evolution of the four-engine aircraft, from its inception to its ultimate success.

In the early 1950s, jets ushered in a revolution in commercial aviation-the birth of the jet age. Before that, long-haul flights were mainly on piston-engine propeller aircraft [4]. Due to the relatively poor reliability of piston engines at the time, four engines were used to provide the redundancy needed to ensure the safety of transoceanic flying. That design ethos, of course, extended into the early jet airliners. Furthermore, first-generation jet engines had relatively low thrust; therefore, four engines remained an optimal approach to provide the power needed for takeoff and cruise of large passenger aircraft [5]. Fitting four engines was the only feasible way to obtain the required total thrust to power first-generation long-haul jetliners, such as the Boeing 707 and Douglas DC-8. Hence, the era of the four-engine passenger aircraft was a result of necessity rather than choice.

The first jet airliner in the world to enter commercial operation was the de Havilland Comet of the United Kingdom (see Figure 3), which made its first flight in 1952 and featured four turbojet engines buried in the wing roots [6]. Nevertheless, the Comet's early lead was lost. Between 1953 and 1954, several catastrophic mid-air disintegrations, caused by metal fatigue, severely damaged its reputation and led to its grounding. While this tragic beginning taught invaluable lessons that would inform future aircraft designs, it also paved the way for the rise of American manufacturers.

Following the Comet, U.S. aircraft manufacturers Boeing and Douglas soon introduced their own four-engine jet airliners. The Boeing 707, a four-engine design with engines suspended in pods beneath the wings, entered service in 1957 and became the template for nearly all subsequent large passenger aircraft. The Douglas DC-8 closely followed it. Two architectures, the 747 and the A380, evolved from four turbofan engines, a direct consequence of technological limitations [5]. Nevertheless, due to their phenomenal performance and reliability, these two aeroplanes soon came to dominate the global aviation market and ushered in the era of transatlantic and transpacific jet travel. Four-engine long-haul airliners provided the backbone of the international network at this time, quadrupling the speed of global travel and expanding the possibilities for international trade and cultural exchange.

Commercial aviation, the Boeing 747. In 1969, the 747 was to be the icon of this decade. Its four Pratt & Whitney JT9D engines provided the necessary power to overcome its massive size, length, shape, and distance, "rewarding" us with air travel. Crucially, regulatory constraint played into the quadjet's advantage. Aviation authorities imposed strict Extended-range Twin-engine Operational Performance Standards (ETOPS) regulations, which initially prohibited two-engine planes from flying farther than 60 minutes from an alternate airport. "That rendered four engines an operational and regulatory necessity for long overwater routes, securing a market for aircraft like the 747 and later the Airbus A340" [7].

By the 1990s, with engines advancing rapidly and ETOPS becoming much less restrictive, the range and efficiency of twin-engine airliners had improved to the point that they were gradually taking market share from four-engine aircraft. However, the European manufacturer Airbus retained confidence in the market for large aircraft for hub-to-hub services. In 1993, Airbus also launched the A340, which aimed to surpass the Boeing 747 in fuel efficiency. In 2005, Airbus raised the bar even higher with the all-new double-deck A380 "superjumbo". It again held the record for size and payload in commercial aviation as the last hurrah of four-engine airliners.

2.3. Advances in engine technology

What led to the gradual replacement of four-engine aircraft by twin-engine aircraft? Section 2.3 presents an analysis of this subject through engine performance to explain the rise of two-engine aircraft and the drawbacks of four-engine aircraft, which ultimately led to their discontinuation.

2.3.1. Disadvantages of the four-engine aircraft

Even though four-engine aircraft were highly valued in the early jet age for their power redundancy and thrust advantages, over time, their inherent economic drawbacks became increasingly evident. From the aspect of engine performance, it was mainly due to the high fuel consumption.

To mount four engines under the wings, the size and diameter of each engine are constrained. This results in relatively low bypass ratios (the ratio of the mass flow rate of cold air passing through the fan to the mass flow rate of hot air passing through the core) for the four-engine aircraft. It primarily dictates propulsive efficiency, thereby determining the engines' fuel economy [8]. Fuel is one of the largest operating costs of the airlines and therefore, the demand of alternatives with increased fuel efficiency. Also, the wing design was to include four engines, which added to the structure weight of the fuselage. The four-engine aircraft have a relatively large deadweight because of the increased weight in the structure and the number of engines [8]. Deadweight is the weight that is in an aeroplane but will not produce lift or thrust without constant maintaining force and has to be carried throughout the flight period and the aeroplane will consume extra fuel to sustain it. This consequently resulted in massive strain on the spending of airlines due to the high consumption of fuel.

On the other hand, four-engine aircraft also face the challenges of interference drag [9]. Interference drag occurs when two components on an aeroplane are connected, causing airflow interference between them. It will disrupt the initially smooth, streamlined flow, generating additional eddies and increasing drag, thereby lowering aerodynamic efficiency.

2.3.2. Comparison of four and two-engine aircraft

Over the years, twin-engine aircraft have improved in many areas. The tremendous advancements in engine technology are among the most significant developments in two-engine aircraft.

The technology of modern high-bypass turbofan engines has advanced significantly. Taking thrust as an example, the Pratt &Whitney JT3D engine used in the Boeing 707 in 1958 provided approximately 17,000 pounds of thrust per unit, while today's General Electric GE9X engine, used in the Boeing 777, delivers over 134,000 pounds of thrust per unit [10]. The power of a single modern high-trust engine even exceeds the combined output of the four engines on early four-engine aircraft. Additionally, thermodynamic efficiency has increased from approximately 30% in the early jet age to over 50% today, with future improvements anticipated through incremental refinements rather than revolutionary breakthroughs.

Besides, from a fuel-efficiency perspective, two large engines are generally more efficient than four smaller ones. Larger engines feature higher bypass ratios. It determines the engine's fuel economy during subsonic cruise. Moreover, superior thermodynamic cycle efficiency means that, for the same total thrust output, twin-engine aircraft consume less fuel. According to research by the International Council on Clean Transportation (ICCT), in 2016, huge four-engine aircraft operating on transpacific routes were 24% less fuel-efficient per passenger than their twin-engine counterparts [8]. Specifically, the Boeing 747-400 consumed significantly more fuel per flight hour compared with similarly sized modern twin-engine aircraft. During periods of high fuel prices, this translates directly into substantial operating cost pressures (see Figure 3).

Figure 3. Difference from industry average fuel efficiency of 31pax-km/L for 14 aircraft types used on transpacific routes, 2016 [8]

2.4. Other factors impacting the viability of the four-engine aircraft

Some non-technical factors also impact the viability of the four-engine aircraft. This section presents an analysis of discontinuation from the perspectives of economic factors and regulatory effects.

2.4.1. Economic factors

Engine-related maintenance accounts for a significant share of total aircraft maintenance costs. Four-engine aircraft, on the other hand, have four engines and four sets of related systems like fuel, hydraulic, and electric systems, so their maintenance and spare parts needs are much higher than those of twin-engine planes. From ordinary inspections and scheduled overhauls to unscheduled repairs, each task of maintaining the multiengine planes is that much more expensive. This translates to the long-term own cost of four-engine aircraft being substantially higher than that of twin-engine aircraft [11].

Besides, a four-engine design dictates operation on ultra-long-range routes. These routes are characterized by extended flight hours per leg, which consequently leads to high total accumulated flight hours. In the article "Analysis of Aircraft Maintenance Processes and Costs" [12], the analysis of aircraft operational performance relies on key data, including maintenance cost, flight hours, flight cycles, dispatch reliability, and pilot-reported defects. Maintenance costs have the greatest correlation with flight hours; hence flight hours are the most relevant means. Although the relationship between flight cycle and costs is not very robust, the reliability of dispatch is also negatively correlated with cost. The data of Airline X (2014-2018) were used in this research as the fleet was represented by six aircraft types, such as A340-600 and A320-200. The highest maintenance costs were incurred by the A340-600, the wide body aircraft that is currently doing long haul services, which contributed 25 percent of the total and the highest number of flight hours were also recorded in the A340-600, which contributed 21 percent of the total flight hours. Moreover, the A340-600 had the lowest dispatch reliability (97.13%), underscoring a significant maintenance issue. Analysis is shown in Figure 4, Figure 5 and Figure 6.

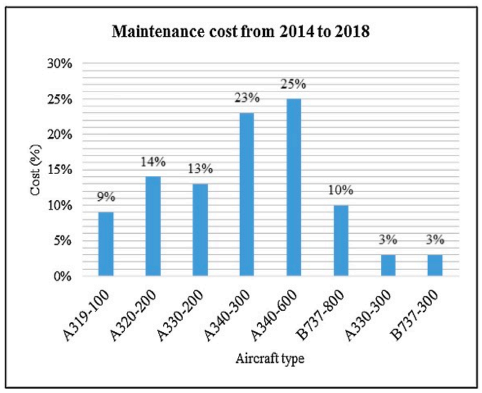

Figure 4. The maintenance cost [12]

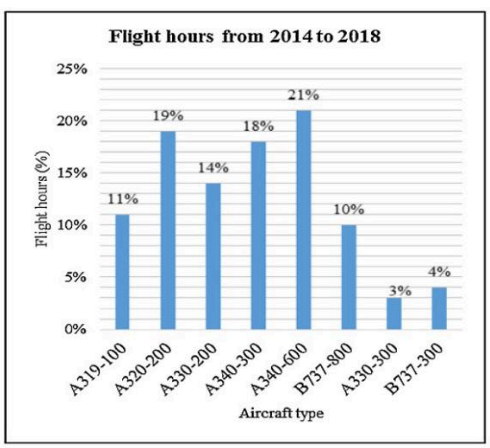

Figure 5. The fight hours [12]

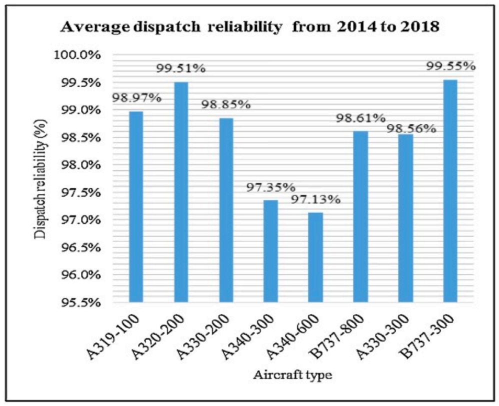

Figure 6. The average dispatch reliability [12]

On the other hand, large four-engine long-haul aircraft, such as the Boeing 747 and Airbus A380, were initially designed to carry large numbers of passengers between major "hub-to-hub" cities. Still, the global airline market has been moving steadily toward the more flexible "point-to-point" model of operations [13]. In this configuration, they can meet passengers' growing desire for convenience by opening more direct routes and utilising mid-size, wide-body, twin-engine aircraft, such as the Boeing 787 and Airbus A350. The use of large four-engine aircraft on these lower-density routes is typically a struggle to fill, leading to the highest seat costs in the industry and making it the least profitable business proposition. In addition, the airport infrastructure demands related to the jumbo jet, such as the A380 (e.g., runway length and boarding bridges), limit the flexibility of their route systems even further

2.4.2. Legislative factors

Extended-range Twin-engine Operational Performance Standards (ETOPS) is based on a set of technology, equipment, and maintenance requirements developed by regulatory authorities worldwide to govern the operations of twin-engine aircraft. The development and continuous improvement of ETOPS has been crucial in making long-range transoceanic routes accessible to twin-engine aircraft.

Until the 1980s, two-engine aircraft were limited to flying within one hour of a suitable alternate airport. Following the demonstration of improved engine reliability, the FAA authorized 120-minute ETOPS in 1985 and extended it to 180 minutes in 1988. Two-engine planes could now fly the "Oceans and more". Entering the 21st century, with technology evolving, ETOPS standards continued to expand. The Airbus A330 is rated for ETOPS-240, whereas the Boeing 787 and 777 are rated for ETOPS-330 [14]. Airbus' new A350 has also achieved a never-before-granted ETOPS-370 rating, allowing it to fly on one engine for up to 370 minutes (over six hours) to an alternate airport. This enables it to fly practically anywhere in the world, except for areas as extreme as the airspace over the South Pole itself.

3. Discussion

A combination of technological and economic factors drove the discontinuation of the four-engine aircraft. This section aims to identify the interactive effect of technological progress and economic efficiency exerted on the discontinuation of the four-engine planes. This section also analyzes the remaining challenges and future improvements.

3.1. The trade-off between technological progress and economics

Although early four-engine aircraft suffered from limited engine performance and high fuel burn, they also offered genuine technical and operational advantages. Their most obvious strength was capacity: classic four-engine wide-bodies such as the Boeing 747 and Airbus A380 can carry around 550–600 passengers in high-density layouts, making them attractive on bustling trunk routes and at slot-constrained hub airports [15, 16]. Technological progress did not bypass these aircraft. Later variants were fitted with much more advanced engines. For example, the Boeing 747-8 uses the GEnx-2B, which employs carbon-fibre fan blades and improved aerodynamics to deliver around 66,500 pounds of thrust with lower specific fuel consumption than earlier engines [17, 18]. On paper, these improvements appeared to keep four-engine aircraft competitive by combining large capacity with more efficient propulsion.

However, when the economic context is examined in detail, the picture becomes less favourable. Even with upgraded engines, four-engine aircraft still carry two extra engines compared with comparable twin-engine types. Each additional engine adds weight, drag, and maintenance complexity. Studies of transpacific operations suggest that large four-engine jets remain roughly 20–25 per cent less fuel-efficient per passenger than the best twin-engine aircraft on similar routes [8, 19]. Higher fuel burn translates directly into higher operating costs at a time when fuel can represent a third or more of an airline's expenditure and when aviation is under pressure to cut carbon emissions. Maintenance costs also scale with the number of engines: more engines mean more inspections, overhauls, and spare parts inventory [11, 12]. Economically, four-engine aircraft therefore require very high, consistently full load factors to spread these costs across enough passengers, which is difficult to achieve outside a small number of flagship routes.

The fundamental trade-off between technological progress and economics emerges when four-engine advances are compared with twin-engine progress. High-bypass turbofan development has allowed modern twin-engine wide-bodies such as the Boeing 787 and Airbus A350 to offer long-haul range, high reliability, and excellent fuel efficiency, while carrying 250–350 passengers more flexibly across many routes [10, 14]. For airlines, the choice is therefore not between "old" and "new" technology, but between two different ways of using technology to create value. Investing in ever more capable four-engine aircraft delivers impressive technical performance. Still, it locks operators into high fixed and variable costs justified only for a narrow set of routes. Investing in an efficient twin-engine plane, by contrast, sacrifices some peak capacity but delivers lower per-seat costs, reduced environmental impact, and greater network flexibility, especially for point-to-point services [13]. The eventual discontinuation of four-engine passenger aircraft shows that, in this case, economic considerations and environmental pressures outweighed the benefits of further technological refinement of the quadjet concept.

3.2. Key reasons for discontinuation of the four-engine passenger aircraft

The disappearance of four-engine passenger aircraft from mainstream fleets was not caused by a single technical breakthrough but by the interaction of several trends. Initially, four engines were a rational response to the limitations of early turbojets: each unit delivered modest thrust and had relatively low reliability, so long-haul aircraft needed four engines both to meet take-off performance requirements and to provide redundancy on transoceanic routes [5, 15]. Under strict early ETOPS rules, only quadjets could legally operate many over-water sectors. In this context, large aircraft such as the Boeing 747 and, later, the Airbus A380 allowed airlines to exploit economies of scale on hub-to-hub routes by carrying very high passenger loads in a single flight.

As engine technology advanced, the assumptions that justified this layout began to erode. Modern high-bypass turbofan engines deliver far higher thrust and much better thermal efficiency, so two large engines can now provide the same or greater performance than four smaller ones [10]. At the same time, the four-engine layout imposed structural and aerodynamic penalties: heavier wings to carry four engine pylons, higher "deadweight", and additional interference drag, all of which increased fuel burn [8, 9]. Because fuel is one of the highest operating costs, these structural disadvantages translated directly into higher cost per seat and higher carbon emissions, just as regulators and the public were paying more attention to aviation's environmental impact. Expanded ETOPS rules removed the regulatory need for four engines on most long-haul routes, so the redundancy advantage that once justified higher costs largely disappeared [14].

Economic and operational factors reinforced this technological shift. Maintenance studies indicate that long-haul four-engine aircraft, such as the A340-600, incur disproportionately high maintenance costs and exhibit lower dispatch reliability when compared to smaller twin-engine aircraft. Primarily, they require four sets of complex systems and accrue high flight hours on ultra-long-range missions [11, 12]. At the same time, airline business models have also changed to be less hub-and-spoke and more point-to-point networks. Mid-sized twin-engine wide-body aircraft, such as the Boeing 787 and Airbus A350 can open thinner routes between secondary cities, making it easier to achieve high load factors without relying on large hubs [13]. In contrast, huge four-engine jets are difficult to fill on anything other than the densest city pairs, leading to high seat-mile costs and poor profitability; their demanding airport infrastructure requirements further restrict where they can operate.

Taken together, these developments mean that four-engine airliners no longer sit at an efficient point in the trade-off between performance, cost, and flexibility. A small number of quadjets remain in service on niche routes or as freighters, showing that the configuration can still be helpful in specific circumstances. However, for mainstream passenger operations, improvements in twin-engine technology, changing regulations, and evolving network strategies have combined to make the four-engine layout commercially unsustainable.

3.3. Future outlook

Although twin-engine aircraft have made a considerable contribution to aviation, the pursuit of more efficient, sustainable, and capable aircraft continues to face several challenges. This section outlines the remaining challenges and analyzes areas for improvement.

3.3.1. Key remaining challenges in passenger aircraft

Despite the impressive progress of modern twin-engine airliners, several engineering and environmental constraints mean that today's designs are much closer to the limits of conventional gas-turbine technology than early jet aircraft were. First, there are clear signs of diminishing returns in fuel-burn improvements. For the last few decades, most gains have come from steadily increasing the bypass ratio and overall pressure ratio of turbofan engines. Higher bypass ratios improve propulsive efficiency, but they also require larger fan diameters and nacelles, which add structural weight, nacelle drag, and ground-clearance issues, as well as stronger landing gear and wing structures [9]. At the same time, core components such as compressors, combustors, and turbines are already operating at temperatures and pressures close to the limits of current nickel-based superalloys and cooling technologies [20]. New materials, such as ceramic matrix composites, can push these limits further, but they are expensive, difficult to manufacture at scale, and introduce new inspection and repair challenges. In other words, each extra percentage point of thermal efficiency now requires disproportionately higher cost and engineering complexity [21].

Reliability is another area where progress has created new types of risk rather than eliminating risk. ETOPS-certified twin-engine aircraft now routinely operate long transoceanic sectors on the assumption that catastrophic engine failures are infrequent. However, experience shows that "common-cause" failures can still occur, for example, due to manufacturing defects, design flaws, or maintenance errors that affect both engines in a fleet. The Trent 700 fan-blade incident on an AirAsia X A330, which led to an in-flight shutdown and subsequent redesign, illustrates how a single technical issue can affect the entire engine family and its safe operating margins [22]. The challenge is therefore not simply to make individual engines reliable, but to manage system-level risks in global fleets that depend almost entirely on twin-engine long-haul operations.

A third cluster of challenges arises from the transition to low-carbon aviation. Current high-bypass turbofan engines are optimised for conventional jet fuel, and even "drop-in" Sustainable Aviation Fuels (SAFs) can affect combustion characteristics, fuel-system behaviour, and lifecycle emissions in complex ways. More radical options, such as liquid-hydrogen propulsion or hybrid-electric architectures, demand a fundamental redesign of the engine core, fuel tanks, airframe layout, and thermal-management systems [23, 24]. With current battery and hydrogen storage technologies, energy density remains far below that of kerosene for large, long-haul aircraft, so designers must trade off range, payload, and safety margins against any potential emissions benefit. This means that, for the foreseeable future, large gas-turbine engines will continue to dominate long-distance passenger aviation, locking in a significant level of CO_2 emissions.

Finally, even if CO_2 intensity per passenger-kilometre continues to fall, non-CO_2 climate and environmental impacts remain a major unresolved issue. High-altitude contrails and the induced cirrus clouds they form can have a radiative forcing effect comparable to, or larger than, the CO_2 emitted by the same flight over shorter time horizons [25]. Nitrogen Oxides (NO_x) produced in the hot core also alter atmospheric chemistry, making mitigation difficult with existing combustor designs. At the local level, aircraft noise during take-off and landing continues to generate conflict between airports and surrounding communities. Modern high-bypass engines are quieter than earlier turbojets, but further reductions often require larger, slower fans, acoustic liners, and operational restrictions, all of which incur extra cost and design constraints [26, 27]. As a result, environmental regulation is likely to tighten faster than engine technology can improve, turning noise and non-CO_2 effects into binding design constraints for future passenger aircraft.

3.3.2. Future improvements

Given the technical and environmental limits identified in the previous section, many proposed "future improvements" to passenger aircraft engines can be seen as attempts to push beyond the constraints of the conventional high-bypass turbofan, rather than simple extensions of existing trends. One prominent concept is the open-rotor engine (see Figure 7). By removing the nacelle and using large, contra-rotating propeller blades, open rotors aim to achieve propulsive efficiencies that are difficult to reach with ever-larger ducted fans, potentially reducing fuel burn by around 15–20 per cent compared with current turbofans [28]. This idea directly addresses the bypass-ratio "ceiling" described earlier, offering a way to increase the adequate mass flow without adding excessive nacelle weight and drag. However, open-rotor designs also introduce serious challenges in noise, vibration, and safety perception, and there is uncertainty over whether they can meet future community noise limits or be accepted by passengers on long-haul flights. In that sense, they illustrate a wider theme: the most radical efficiency concepts often involve trade-offs that are difficult to reconcile with airport, regulatory, and market constraints.

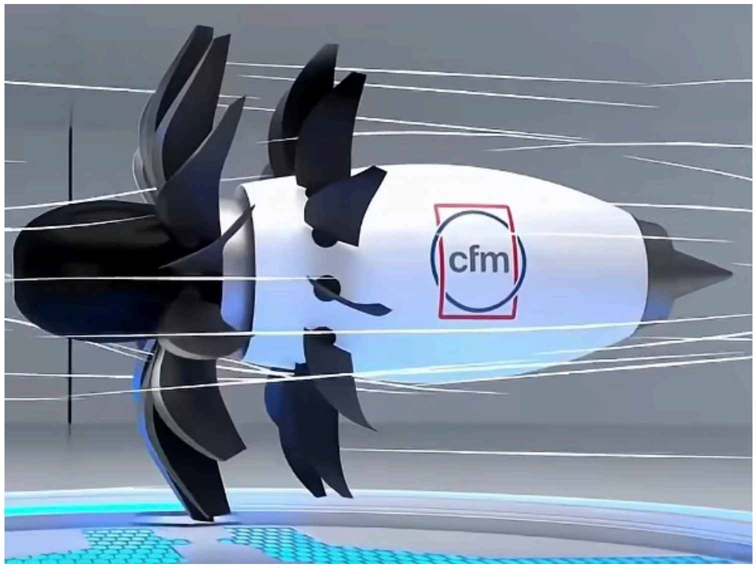

Figure 7. An image of an open rotor engine [29]

A second area of enhancement focuses on how engines are designed and manufactured, rather than their overall configuration. Advanced manufacturing techniques such as additive manufacturing (3D printing) enable engineers to produce lightweight components with intricate internal cooling passages or optimized fuel manifolds that would be impossible to machine through traditional methods. These techniques can diminish weight, enhance cooling efficiency, and optimise combustion, squeezing a few extra percentage points of efficiency and reliability of gas-turbine cores. At the same time, they raise concerns regarding inspection, repair, and certification, given that complex printed geometries may exhibit different behaviours under fatigue and damage than conventional parts. Similarly, new materials, such as ceramic matrix composites, promise higher-temperature capability and lower weight, but they remain expensive and challenging to produce at the scales required for civil fleets [20]. As a result, these improvements are likely to deliver incremental gains rather than a complete step-change, and their adoption will depend on whether the additional manufacturing cost is justified by fuel savings over the engine's life.

More transformative proposals aim to change not just how thrust is produced, but how it is distributed and powered. Turbo-electric or hybrid-electric architectures, for example, envisage a gas-turbine core operating primarily as a generator, supplying electricity to multiple fans distributed across the wings [30]. In theory, this allows the core to run at its most efficient operating point while the fans are placed where they produce the most useful thrust and boundary-layer control. In practice, the benefits must be weighed against the mass and complexity of generators, power electronics, and cabling, as well as the low energy density of current batteries and alternative fuels. For large, long-haul aircraft, today's electrical and hydrogen technologies are unlikely to replace kerosene entirely in the near term; most industry roadmaps therefore see Sustainable Aviation Fuels (SAFs) and more efficient gas turbines as the primary tools for reducing lifecycle emissions over the next few decades [19].

Overall, future improvements in passenger aircraft engines are best understood as a portfolio of partly competing, partly complementary options rather than a single "silver bullet". Concepts such as open rotors, advanced materials, additive manufacturing, hybrid-electric systems, and SAFs all address different aspects of the challenges identified in Section 3.3.1. Still, each carries its own technical risks, cost implications, and regulatory uncertainties. For the research question in this dissertation, the key point is that even after more efficient twin-engine designs have replaced four-engine aircraft, significant further innovation will be needed to meet tightening climate and noise targets. Any realistic future pathway is likely to combine incremental refinements to gas-turbine cores with selective adoption of disruptive technologies on specific aircraft sizes and route types, rather than a rapid, uniform transition to an entirely new propulsion system.

4. Conclusion

The proposed dissertation seeks to answer two main questions: firstly, why have four-engine passenger planes been discontinued, and, secondly, what has changed in terms of technology relating to engine design that allows the substitution of a four-engine aircraft with a twin-engine one and, yet, leaves the key challenges to be resolved during the further advancement. Based on technical literature, industry reports and historical case studies, the analysis has proven that early quadjets like Boeing 747 and Airbus A380 were originally necessitated by need. At a time when early jet engines provided minimal individual thrust and had a rather low reliability, four engines were all required to provide sufficient performance and redundancy of safety, particularly in flights over oceans and more distant areas. Also, these large planes helped in economies of scale in the conventional hub-and-spoke networks by concentrating passenger traffic in large hubs. With time though, the technical and economic drawbacks of the four-engine system became too evident. Structurally, a wing structure with four engine nacelles necessitates a heavier and more complicated wing structure which leads to higher weight and aerodynamic drag interference effects. Operational wise, keeping four full power units required four sets of fuel, hydraulic and electrical systems, thus required regular inspections and service, thus increasing maintenance labour and long-term expenses. The radical move in the market came because of the drastic improvements in the turbofan high bypass technology that increased engine thrust, thermal efficiency and reliability, making it possible to fly with twin engines safely with a range and payload that was previously achievable by only quadjets. This technological leap, coupled with the progressive relaxation of ETOPS rules, enabled twin-engine aircraft (such as the Boeing 787 and Airbus A350) to fly virtually any long-haul route with significantly lower fuel consumption per seat and vastly simpler maintenance. This better aligns with the modern preference for flexible point-to-point demand patterns, confirming the commercial withdrawal of four-engine aircraft.

The analysis also explicitly showed that these developments do not signify that the engineering challenge of long-haul flight has been conclusively "solved". Conventional gas-turbine technology is now close to several hard physical and practical limits. Further increases in bypass ratio are constrained by fan size, added weight, and nacelle drag, while core temperatures are already near the limits even of advanced materials such as ceramic matrix composites. At the same time, climate policy and public opinion are shifting attention away from small efficiency gains towards absolute cuts in CO_2 and non-CO_2 climate impacts. The potentially disruptive alternatives, such as open-rotor engines, hybrid-electric propulsion, and widespread utilization of Sustainable Aviation Fuels (SAFs) have a promising cut in emissions. Still, each of them has their own set of problematic trade-offs in regards to noise, safety certification, energy density, cost, and infrastructure. The timeline of the four-engine so-called quadjet is a vivid lesson that even legendary technologies are discarded as soon as they cease to comply with the economic conditions, engineering development, or even references to the regulations. Further studies, therefore, must transcend the abstract discourse and be more dependent on quantitative research. This is the document contains the extensive modelling of drag and structural weight, sound Direct Operating Cost (DOC) comparisons and realistic assessment of the technical maturity, certification issues, and infrastructure requirements of new propulsion concepts and fuels. The next generation of airliners can only achieve this by striking the balance between performance, economic viability, and environmental responsibility to evade the same fate as the quadjet.

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