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Aircraft Propellers—Is There a Future? †

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Abstract: The race for speed ruled the early Jet Age on aviation. Aircraft manufacturers chased faster and faster planes in a fight for pride and capability. In the early 1970s, dreams were that the future would be supersonic, but fuel economy and unacceptable noise levels made that era never happen. After the 1973 oil crisis, the paradigm changed. The average cruise speed on newly developed aircraft started to decrease in exchange for improvements in many other performance parameters. At the same pace, the airliner's power-plants are evolving to look more like a ducted turboprop, and less like a pure jet engine as the pursuit for the higher bypass ratios continues. However, since the birth of jet aircraft, the propeller-driven plane has lost its dominant place, associated with the idea that going back to propeller-driven airplanes, and what it represents in terms of modernity and security, has started a propeller avoidance phenomenon with travelers and thus with airlines. Today, even with the modest research effort since the 1980s, advanced propellers are getting efficiencies closer to jet-powered engines at their contemporary typical cruise speeds. This paper gives a brief overview of the performance trends in aviation since the last century. Comparison examples between aircraft designed on different paradigms are presented. The use of propellers as a reborn propulsive device is discussed.

Keywords: propeller; aircraft; turboprop; flight efficiency; flight speed

1. Introduction

The propeller is a device that converts the rotary power of an engine or motor into a thrust force that pushes the vehicle to which it is attached. Comprised by one or more radial airfoil-section blades rotating about an axis, the propeller acts as a rotating wing. Aircraft propellers first emerged at the end of the 18th century; however, this study only discusses its history from the 20th century and beyond. See Ref. [1,2] for a historical review from the preceding decades. By the end of the 19th century, a feeling of disbelief on heavier-than-air manned flight was present [3]. The first controlled, powered flight, starred by the Wright Brothers in 1903, marked the turn of a page of skepticism concerning heavier-than-air manned flight. This remarkable achievement brought an increased excitement around the aviation community, and in the period 1905–1910, there was an impressive growth in the number of filed patents [4] (see Figure 1).

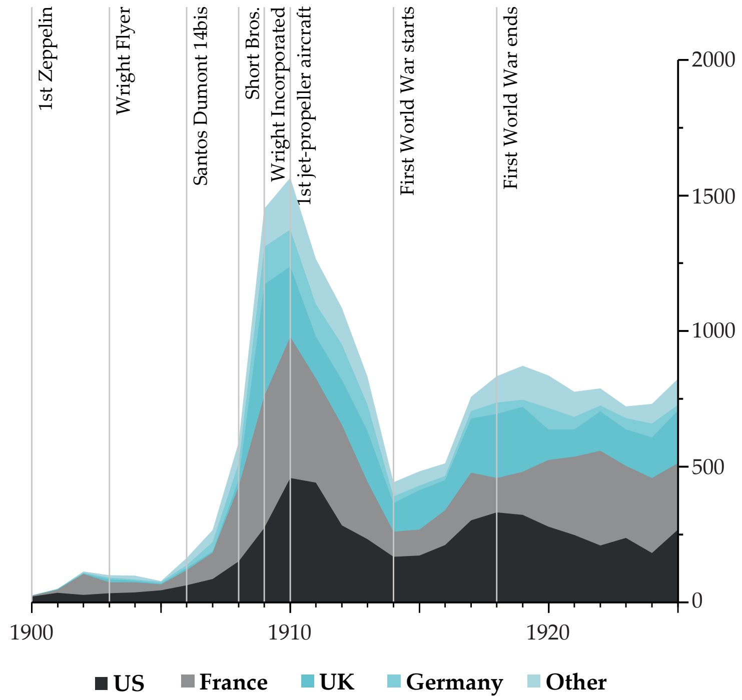


Figure 1. First patent filings by origin, 1900–1925. Between 1900 and 1970, patent filings relating to aviation tended to concentrate in the US, France, Germany, and the UK. Source: adapted from [4].

This pre-WWI (World War I) period was also responsible for a transition from individuals as hobbyists and enthusiasts, motivated by curiosity, pride, and fame, to institutions and governments acknowledging the airplanes as a strategic weapon to win wars. By the end of WWI, from the 1920s to the 1930s, designers, engineers, and inventors established new, active, and venturous aeronautic communities in Europe and North America. This prosperous era of innovation and technological growth of aviation extended its developments to all components of the airplane, including the propeller. Donald W. Douglas, head of the Douglas Aircraft Company, considered those communities of people responsible for helping change the world, acknowledging propeller makers and their creations indispensable for success [5]. The work on those propulsive devices joined the higher power outputs of the newer engines to the improved body aerodynamics resulting in higher performance aircraft capable of "climb quicker and cruise faster using less power and if need be, fly to safety on one engine" [3]. Since the first effective propellers powered by piston engines, through impressive supersonic aircraft and up to modern airliners, a lot has changed in aviation. The aircraft is now a balance between hundreds of different specifications. Some being improved at the cost of others. Today, the advent of electric multirotor vertical take-off and landing aircraft [6–11], starting as unmanned aerial vehicles but also aimed for personal transportation are bringing the assertion of the propeller as the main choice for low-speed, state-of-the-art efficient propulsion devices. Nevertheless, propellers are nothing more than a niche in commercial aviation commute aircraft. However, this century brought new challenges and priorities. Global warming, pollution, and sustainability are now serious concerns [12]. The present work shows the evolution of cruise speeds, especially on commercial aviation, in the past century to realize that the propeller comeback may be the next innovation towards more sustainable aviation. The trends are presented, and their motives are discussed. In the first section, a brief historical overview is presented. The second section introduces the influence of the cruise speed in the aircraft aerodynamic efficiency and engine fuel consumption. Then it discusses the evolution of the flight speed of the airliners since the jet age. The third section shows the relevance of bringing back the propeller and continue its development.

2. Early Jet Age: The Race for Speed

With the invention and development of the jet engine during WWII, gas turbine-powered aircraft expanded the whole flight envelope. Flying higher and faster, both commercial and military jet airplanes ruled the 1950s and 1960s, at what was called: The Jet Age [13]. Compared with piston airplanes, the speed and ceiling of these first jet-powered aircraft were incredible, and the race for flight speed became the leading trend [3]. The following years gave birth to a generation of even faster jet aircraft as the example of the Boeing 727, which had a maximum cruise speed of Mach 0.84. However, to overcome the speed of sound, a larger amount of power was required. This is due to the sharp rise in drag, experienced above a critical Mach number [14] (Figure 2). Also, supersonic flight introduced the need for pure jet engines since the propeller blades encounter the critical Mach number at smaller cruise speeds due to their additional rotation speed.

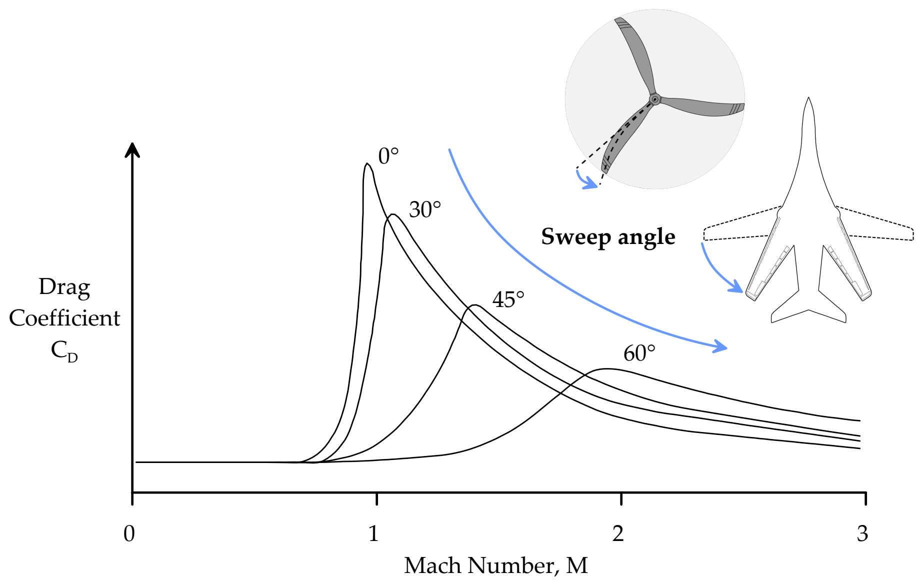


Figure 2. Drag rise due to cruise Mach and the effect of wing sweep. Adapted from [15].

Therefore, the race continued, and in the early 1960s, the Convair 990 could already fly at speeds up to Mach 0.87 [16]. At this time, in one of the test flights, Douglas company accelerated its DC-8 to Mach 1.01 in a 16-second dive. Nevertheless, commercial aviation did not stop there. Pursuing military achievements as the Lockheed SR-71 "Blackbird", that cruised at Mach 3.2, commercial aviation needed to rush forward. In the early 1970s, jet engine technology was developing at a tremendous pace. Commercial aircraft, characterized by sharp noses and high swept wings, also started breaking through the sound barrier. The Concorde and the Tupolev Tu-144 were developed to cruise at Mach 2. However, Mach 2 still seemed not enough, so, Boeing wanted to create an even faster commercial airplane [17–19], aiming to fly at Mach 3. Suddenly hypersonic transportation was the subject of research [20,21]. It seemed that there were no limits to the race for speed, but something went wrong, and the true supersonic age never came. The magnificence of supersonic airliners was comparable only to the horror of their ecology and economy. The supersonic engines roar was annoying to the cities' populations. Sound booms were destroying everything around [22], leading many countries to ban supersonic flights from their airspace [23]. In addition to that, the super-powerful afterburner engines were so hungry for fuel that airlines had to increase the cost of tickets to cover their expenses. Those facts, combined with the 1970s oil crisis, made the supersonic flight not to enter mass aviation. To transport ordinary travelers on such planes was the same as the average citizen commuting to work on supercars. One of the main reasons that made the airlines and manufacturers abandon the race for speed is also one of the main elements of the aircraft: the engine. The heart of most modern aircraft is a jet engine. The task of any jet engine (or reaction engine) is to convert the fuel's chemical energy into the jet flow's kinetic energy. In practice, the fuel ignites, expands, accelerates, and pushes the machine forward. The jet engines used in aviation use not only their fuel but also the surrounding air, which is also heated up and accelerated to be ejected at high speed by a nozzle to create thrust. See Ref. [24] for further insights on jet engines. The Rolls-Royce / Snecma Olympus 593 that equipped the Concorde is a classic example turbojet engine. However, these engines were very greedy. With its small capacity, Concorde had a huge fuel consumption, resulting from the great increase in drag shown in Figure 2. The much larger Boeing 747, produced in 1968, turned out to be much more economical [25]. Despite that, new larger subsonic jet-powered airliners conquered the main long-haul routes, and smaller models were conquering the regional ones.

3. Fuel Efficiency

For commercial aircraft, fuel efficiency is usually regarded as the inverse of the fuel consumption, which is fuel quantity burned per unit traveled distance per unit passenger, normally, in $kmPax/L_{Fuel}$. When comparing different fuels, fuel mass is more meaningful than fuel volume. If, instead of mass or volume of fuel, the amount of energy consumed (or contained in that mass of fuel) was used, one could even compare different types of propulsion systems, e.g., the electric propulsion. Considering the propulsive system efficiency as $\eta_{th}\eta_p$, where η_{th} is the thermal efficiency and η_p is the propulsive efficiency, and that in cruise, the required thrust is:

$$F = \frac{W}{L/D} \tag{1}$$

where F is the propulsive thrust force, W is the aircraft weight, L and D are aircraft lift and drag, respectively.

Using Equation (1), the aircraft fuel efficiency can be regarded as:

$$\eta_{Fuel} = \frac{L}{D}\frac{pax}{W}\eta_{th}\eta_p \tag{2}$$

Therefore, the aircraft will be fuel-efficient if it has large aerodynamic efficiency (L/D) and low take-off weight per unit passenger (W/pax). The aerodynamic efficiency depends mostly on the airfoil design and wing design parameters: span; chord; sweep; etc., and all other elements of the aircraft that generate drag but not produce any lift. The weight per unit passenger depends mostly on the aircraft structure, materials, and design. The engine thermal efficiency has been improving in recent decades being close to its upper limits. Regarding the propulsive efficiency, to propel the aircraft, the propulsive system generates the thrust by accelerating the incoming air stream mass flow from V_{Cruise} to a propulsive stream with V_{Jet}, considering that the fuel mass flow is much smaller than this propulsive stream, we get Equation (3).

$$\eta_p = \frac{2}{2 + \frac{F}{\dot{m}V_{Cruise}}} \tag{3}$$

with $\dot{m}$ being the propulsive stream mass flow rate.

According to Equation (3), the propulsive efficiency increases if $\dot{m}$ is increased. This was accomplished in the jet engine by adding an external bypass outer stream of cold air mass flow. These engines were named turbofans and became a real classic solution in modern aviation. Since their birth, turbofan engines started to replace turbojets, becoming as fast as them, despite that the advantage of adding the bypass cold stream diminishes towards higher V_{Cruise}. Most modern fighters like the F-15, Eurofighter Typhoon, Sukhoi Su-30, and the newest F-22 and Sukhoi Su-57 are equipped with turbofan engines. At V_{Cruise} of current commercial aircraft, the bypass stream fan is in fact a ducted propeller. Figure 3 shows the typical propulsive efficiencies for the most common aircraft engine types. The influence in the propulsive efficiency of parameters such as the propeller blade sweep and engine bypass ratio is also represented. It is clear that the bypass ratio of the turbofan increases the propulsive efficiency relative to the turbojet and that the propeller blade sweep extends the Mach cruise speed limit for propeller operation.

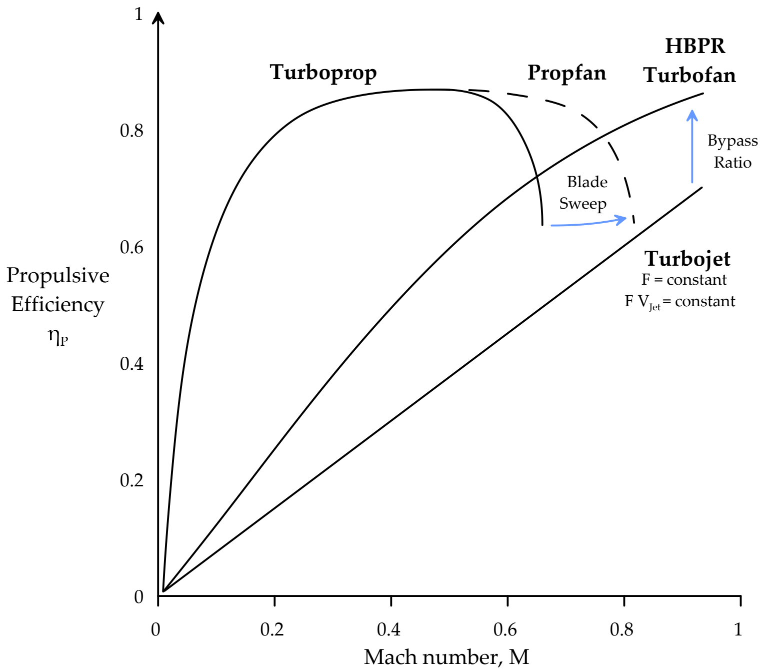


Figure 3. Propulsive efficiency for different engine types.

4. Commercial Aviation—Higher and Faster! Or not?

Although the aviation lemma has typically been higher and faster, in fact, slower commercial aircraft should lead to higher fuel efficiency [26]. Between 1990 and 2010, jet fuel prices have increased over five times, representing about 40 percent of a typical airline's total operating cost [27,28]. As a result, airlines are reviewing all phases of flight to determine how fuel burn savings can be gained in each phase and total.

It is noticeable that since the 1973 oil crisis, commercial airliners are losing their interest in speed from generation to generation (Figure 4). Today, short-haul airliners such as the Boeing 737 and Airbus A320 cruises at airspeeds lower than Mach 0.78. The giant, long-haul flagships like the Boeing 747-8 and the Airbus A380, equipped with four powerful engines, regularly fly at a non-impressing Mach 0.85. Moreover, even the most advanced planes of the modern age as the Boeing 787-Dreamliner and Airbus A350 XWB are not cruising at Mach higher than 0.85. Are the airliners, including the most sublime and advanced of our time, lagging behind the 50-year-old museum exhibits? In the last 50 years, the engines suffered the most noticeable change in aviation. Since the early jet age, engines' bypass ratios increased from 0 to 12.5 (Figure 5). This is easily explained through Equation (3) as engine manufacturers try to increase the engines' propulsive stream mass flow. Modern materials and processes also allowed for higher turbine inlet temperatures and overall pressure ratios. The increase in bypass ratios has been achieved by using bigger fans and fan ducts, which also led to increased empty-weight and parasitic drag. Those factors, associated with rising fuel prices and environmental concerns, are making higher cruise speeds less attractive. In [26], Torenbeek states that "Future long-range airliners optimized for environmentally friendly operation may cruise at no more than Mach 0.75".

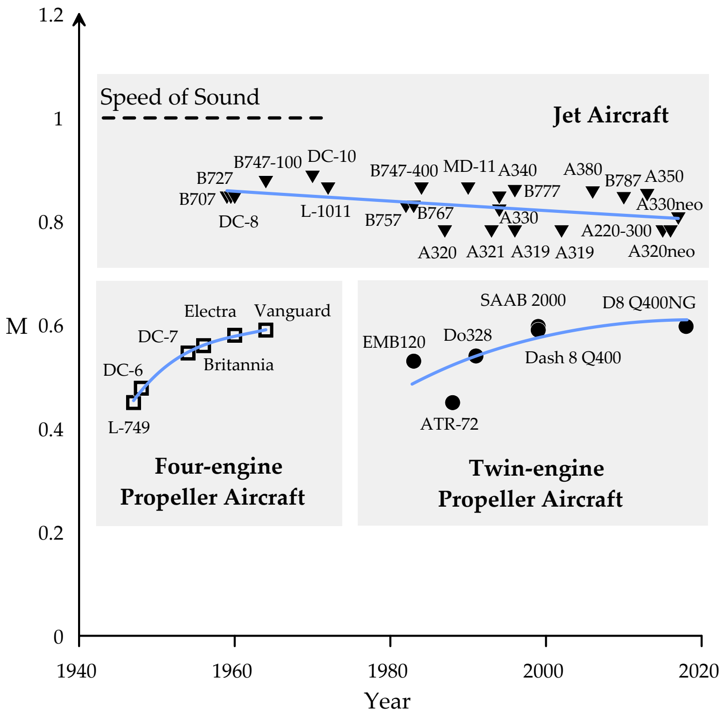


Figure 4. Historical development in maximum cruise speeds for commercial aircraft.

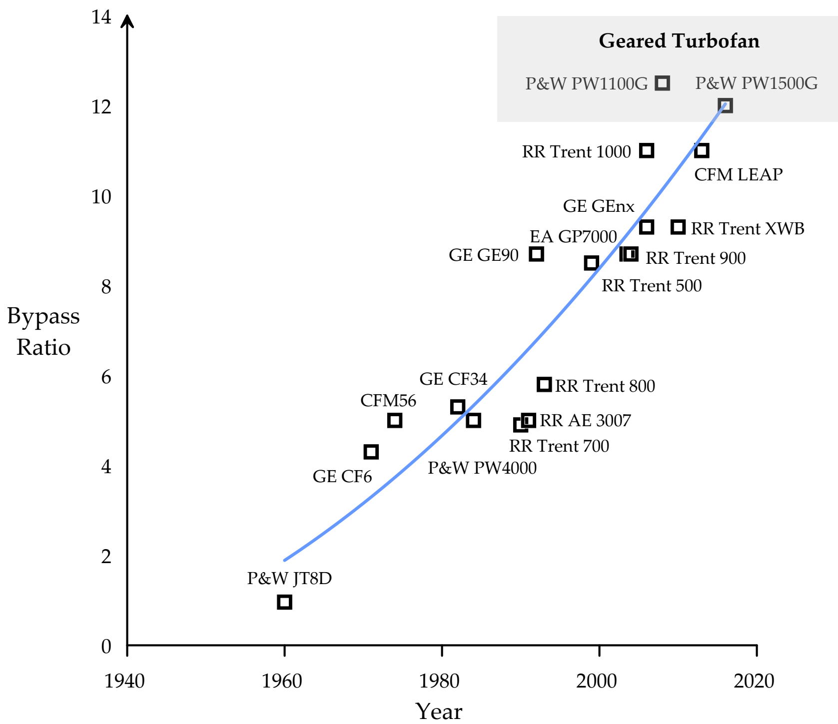


Figure 5. Evolution on the Turbofan Bypass Ratio.

Another noticeable characteristic that confirms this trend of reduced interest in high cruise speeds is the wing design. A comparison of two airliners that operate in the same market segment is presented in Table 1. The wing of Boeing 727 is smaller and has a higher sweep angle than the 737 Max 7. The smaller wingspan and higher wing sweep allow the aircraft to fly faster. When flying near the speed of sound, the airflow accelerates over the wing reaching supersonic speeds and slows down again to subsonic speeds towards the trailing edge of the wing, creating a shockwave and the resulting wave drag. Higher sweep angles delay this effect. The airflow over the wing consists of two components: chordwise flow (parallel to the chord line) and spanwise flow (perpendicular to the chord line). As the only component that suffers the acceleration is the chordwise flow, by reducing the amount of flow in this direction, the aircraft is able to fly faster for the same drag (see Figure 2). Like the newer Boeing 737 Max 7, many other modern airliners have lower wing sweep than their predecessors. This may also be, in part, due to the invention of the supercritical airfoil. However, if the intention were to fly faster, the wing would be kept with a lower span and higher sweep.

Table 1. Boeing 727-200 vs. Boeing 737 Max 7: Technical Specifications. Data from [29,30].

Specifications	Boeing 727-200	Boeing 737 MAX 7
Manufacturing year	1962	2016
Engines	(3×) P&W JT8D-17R	(2×) CFM LEAP-1B
Fuselage length (m)	46.68	35.56
Wingspan (m)	32.92	35.92
Wing sweep	32°	25.03°
MTOW (kg)	95,100	80,286
MMo (Ma)	0.9	0.82
Range–MTOW (Km)	4509	7130
Max Ceiling (m)	13,000	12,000
Fuel capacity (L)	30,620	25,816
Capacity (seats)	155	172

Lower speeds require smaller engine thrust, which represents lower fuel consumption, weight, and noise emissions. Improved efficiency not only allows airlines to save money on fuel but also enables airplanes to fly further. Comparing between the Boeing 727-200 and the 737 Max 7 (described in Table 1), both have similar payload capacities and mass, but the 727-200 has a range of 4500 km, while the 737 Max 7 has 7100 km, twice the range of the former one. In terms of power-plants, the 737 has two engines, while the 727 needed three. The improved take-off thrust of the high bypass turbofan engines was the key to the birth of wide-body airliners, which are the main element of global travel today. However, these high bypass turbofan engines have their drawbacks. All aircraft manufacturers face the same difficulty when upgrading their power-plants. These engines are huge. As the engine manufacturers are raising bypass ratios, the engines' diameter is getting larger, making them harder to fit under the wing of aircraft. The Pratt & Whitney JT8D installed on the 727-200 is much smaller than the CFM Leap-1B that equips the 737 Max 7 (Figure 6). The choice of the Leap-1B to equip the 737 Max 7 also required major upgrades to the landing gear, to maintain the required ground clearance and changes to the wing in order to compensate for the additional engine's weight and drag [31].

The problem is that to adapt the jet propulsion to operate efficiently at lower speeds, the propulsive jet must also have higher mass flow, as observed through Equation (3). Therefore, the turbofan bypass ratio must increase. However, several problems arise when trying to increase the fan size: the fan weight increases; fan noise increases steeply if the peripheral speed is increased to maintain the same shaft rotation speed; reducing the shaft rotational speed such that the noise does not increase, increases the number of stages required for the turbine and thus increases the weight of the core gas turbine. There are a lot more pros than cons to modern aircraft compared to the older airliners. It is a fact that they fly slower, but the rest of their performance is much better, not only due to modern technology but also because of such compromises. In Europe, according to [32], short-haul flights (up to 1500 km) within European Civil Aviation Conference (ECAC) bordering countries represented 78.5% of the total instrument flight rules (IFR) traffic in 2017. According to the same reference, in the United States, the share of short-haul flights reached 80.3% in the same period. Even with the technology that allows us to produce faster airplanes, at those distances, a small increase in speed may reduce flight time but has little impact on the journey. The journey is the wait at the airport, check-in, baggage check, passport control, waiting at the terminal, flight, and again the passport control, baggage claim, and the way from the airport to the destination. All these journey stages will not be accelerated by a higher cruise speed, and all the advantages of flight speed can easily be lost by a traffic jam on the way to the airport. For airlines, the parameters of fuel consumption and life cycle of the aircraft are getting more critical than the cruise speed by the day. Also, fuel consumption is not only money. Fuel tanks on the aircraft remain the same, and flying faster may result in a reduction of range. It is cheaper for the airline to make the passenger more comfortable, show a couple of movies, or provide an extra meal in flight than to speed up the aircraft. From the passenger's point of view, such a deal is also attractive. The flight may be longer, but the level of comfort on those flights is not bad. Higher costs for speed will increase the cost of air tickets, and time is a more valuable resource than money just for a small group of people. The world is ruled by economically optimal airliners with economically optimal performance. A cheaper ticket is more important for a passenger and cheaper operation is more important for airlines. Modern airplanes pursue these goals.

Figure 6. Boeing 727-200 (**left**) side-by-side to a Boeing 737 Max 7 (**right**).

4.1. Present-Day Airliner Speeds

To understand how the typical cruise speeds from the manufacturer compares to the real flight speeds currently being used by airlines, a total of 80 flights were analyzed using Flightradar24. Flightradar24 is a flight tracking service that provides both real-time and stored information about aircraft flights around the world. Specific information such as atmosphere corrected Mach cruise speeds were used to perform this study. Two specific aircraft types were selected: the Boeing 737-800 and the Airbus A320neo. Both aircraft operate short- and medium-haul flights with similar cruise design speeds (with a design Mach cruise speed of 0.785). To compensate for different flight strategies of specific airlines (e.g., low-cost vs full-service), distinct airlines were analyzed for each aircraft type. In Table 2 a synopsis of the analysis is presented.

Table 2. Aircraft analyzed using Flightradar24.

Specifications	Boeing 737-800	Boeing 737-800	Airbus A320neo	Airbus A320neo
Airline	Ryanair	KLM	Wizz Air	British Airways
Registration	9H-QAA	PH-BCK	G-WUKE	G-EUYY
Introduced in	1997	1997	2010	2010
Year of manufacture	2017	2019	2018	2014
V_{Cruise} (Ma) [1]	0.785	0.785	0.78	0.78
V_{Max} (Ma)	0.82	0.82	0.82	0.82
Flights analyzed	20	20	20	20

[1] Design cruise speed announced by the manufacturer.

In Figure 7 the cruise speeds for the total analyzed 80 flights are plotted against aircraft manufacturer announced design cruise speed. From the analyzed flights, it is noticeable that the actual average cruise speed values are lower than the design cruise speed. Regarding the Boeing 737-800, Ryanair presented an average Mach of 0.758 and KLM 0.780. Furthermore, on the Airbus A320neo, Wizz Air average Mach was 0.775, while British Airways registered 0.761. The average Mach cruise speed for the total 80 presented flights is 0.769. Different dispersion can be attributed to distinct weather-related flight optimization, e.g., to account for head or tailwind. Parameters such as airport sockets, aircraft availability, and fuel prices influence each airline's fuel conservation strategies and cost index (CI) . By definition, cost index is the ratio between the time-related operational cost and the fuel cost of an airplane operation, reflecting the relative effects of fuel and time-related operating cost on overall trip cost.

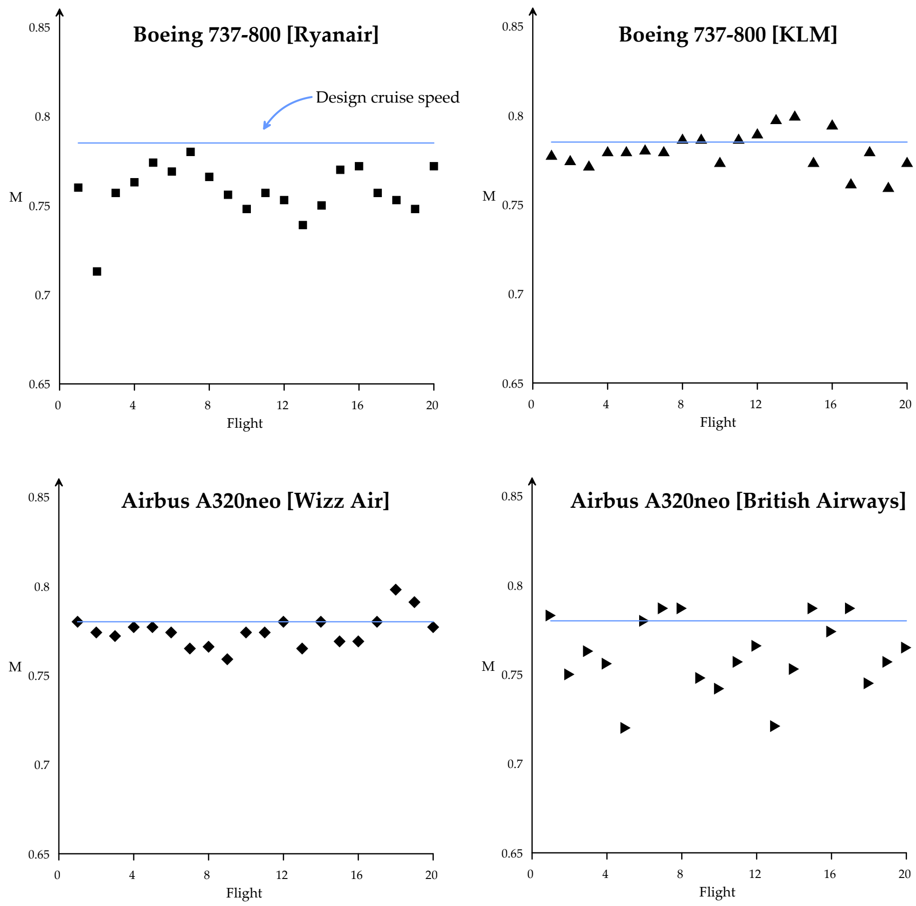


Figure 7. Cruise flight speed from a total of 80 analyzed flights. Boeing 737-800 by Ryanair and KLM. Airbus A320neo by Wizz Air and British Airways. Data sourced from Flightradar24 [33].

From the exclusively propulsive efficiency point of view, referring to Figure 3, one can easily notice that for Mach values of 0.769 the aircraft may already be cruising in a condition where propeller-based propulsive systems, namely propfans, show competitive performance when compared to turbofans [34–36].

5. Propellers Avoidance Phenomenon and the Oil Price Effect

During the jet age, propeller specialists and companies struggled for their place in the industry. After a period of uncertainty, they found it with the development of the turboprop. Since they first emerged in the mid-1940s, turboprop engines were perceived as a temporary compromise between old piston engines and advanced jet engines (see Figure 4, bottom left). This fact resulted in scarce efforts towards technological developments in this type of power-plants and the few turboprop aircraft flying in the late 1960s were still the same built in the 1950s. Though considered rather obsolete, the industry, not seeing great prospects, was not particularly in a hurry to create a replacement for them. In the early 1970s, the use of propeller propulsion in large airframes was almost restricted to the military. However, in 1973, a severe oil crisis [37] started to affect the whole aviation industry. High fuel consumption of the jet engines previously perceived as a perfectly acceptable compromise for speed, associated with prohibitive fuel prices (Figure 8), turned out to be a severe problem. Long-range transportation by large aircraft remained profitable, but flights over short distances by regional vehicles were not often paying off [38]. For the first time in decades, the jet propulsion dominance was questioned, resulting in the industry and governments to chase for more efficient, alternative propulsive systems. This economic environment stimulated work towards a reinvention of the propeller for increased air transportation fuel efficiency.

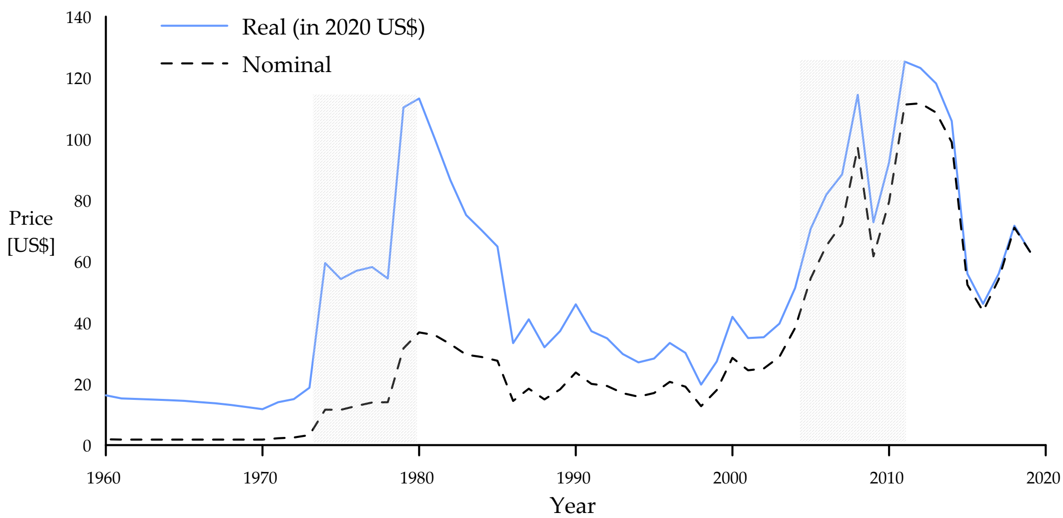


Figure 8. Crude Oil Prices from 1960 to 2020, nominal and real (corrected by the 2019 U.S. inflation). 1960–1985: Arabian Light posted at Ras Tanura; 1986–2020: Brent Spot. Price data source: U.S. Energy Information Administration [39]. U.S. Consumer Price Index (CPI) to correct the prices for the 2019 inflation sourced from the U.S. Bureau of Labor Statistics [40].

5.1. The Advanced Turboprop Project

One of the most remarkable works for increased air transportation fuel efficiency was the Advanced Turboprop Project (ATP) [36]. The ATP was led by the National Aeronautics and Space Administration (NASA) in the 1980s and represented the most relevant and promising work in propeller propulsion up to date. NASA partnering with Boeing and General Electric developed a modern and advanced propeller propulsion system that demonstrated high efficient cruise at Mach 0.65 to 0.80, leading to an overall fuel consumption reduction of 40 to 50 percent relative to turbofans at the time. The flight tests were conducted in a modified B727-100 and McDonnell Douglas MD-80.

Later, Pratt & Whitney, cooperating with Allison, developed an even more efficient geared propfan unit that was tested in an MD-80 (Figure 9). In the 1980s, the Advanced Turboprop Project was developing rapidly, and several new aircraft concepts were being considered for the 1990s. Some of them were engine replacements in current aircraft, while others were new aircraft designs specifically for turboprop/propfan installations.

(**a**) (**b**)

Figure 9. (**a**) Pratt & Whitney-Allison 578–DX geared propfan demonstrator engine, installed on an MD-80 testbed aircraft. (**b**) General Electric GE36 demonstrator engine installed on the Boeing 727 testbed for flight testing in 1986–1987.

In the meantime, new regional twin-engine turboprop aircraft started to appear to compete with the jets that were becoming too expensive to operate, and the interest for turboprop engines rose again (see Figure 4, bottom right). However, as those new turboprop aircraft started to claim the regional routes, a popular resistance, related to the idea of going back to propeller-driven airplanes, and what it represented in terms of modernity and security, started a propeller avoidance phenomenon on the travelers [3]. This negative perception affected the demand for these routes and impacted the economic viability of the turboprop operated routes. At the same time, a sharp drop in fuel prices (see Figure 8) put down all the research efforts in new and advanced propeller design programs like ATP. The turboprop market decreased, and the competition increased.

Jet planes were more expensive, consumed more fuel, and were more demanding on infrastructure but had better flight performance in factors such as cruise speed, range, and comfort, making them more attractive to operators. This fact led to the lowest demand for turboprop airplanes in the civil transportation market [41] making all those efforts to bring the propeller back to medium/long-haul airliners never materialize.

On the other hand, since its appearance, turboprop aircraft conquered the military and defense businesses. Models like the Lockheed C-130 Hercules and the Lockheed P-3 Orion, introduced in the late 1950s, counting with different variants and updated versions, remain in service up to the present. Their versatile airframe and unprecedented capability to use unprepared runways for takeoffs and landings, made those tactical airlifters to spread out among many military forces worldwide. In the 1970s, Lockheed proposed a C-130 variant with turbofan engines rather than turboprops, but the U.S. Air Force preferred the take-off performance of the existing aircraft [42]. Those characteristics associated with all the accumulated military operational experience and improved performance are demanding for the aircraft industry to come with civil, commercial variants. The Lockheed Martin's LM-100J is a civil derivative of the C-130J Super Hercules, the last major update to the military C-130 family. The LM-100J commercial freighter received its type certificate from the Federal Aviation Administration by the end of 2019, and it is expected to enter service by 2020. To answer the demand for the military tactical airlift and compete with C-130J Super Hercules, Airbus introduced the A400M Atlas in 2009. Equipped with four Europrop TP400-D6 turboprop engines, it has a maximum payload capacity of 37 tons, positioning itself between the C-130J Super Hercules and the larger turbofan Boeing C-17 Globemaster.

The growing concern on fossil fuel outage, combined with the global environmental strategy is increasing the oil price, forcing a paradigm shift in the whole transportation industry. New modern, propeller-powered, hybrid aircraft concepts are emerging. The usage of partial electric power-plants introduces part of the solution to one of the most significant handicaps of propellers in the last decades, the increased ground noise levels. Recently, the Electric Aviation Group (EAG) unveiled the HERA concept (see Figure 10), a Hybrid Electric Regional Aircraft with capacity for 70+ seats to be in service by 2028.

Figure 10. EAG Hybrid Electric Regional Aircraft (HERA) (Photo:PRNewsfoto/EAG).

Reinforcing the prominent comeback of the propellers, in 2008, within the Clean Sky program, the European Commission announced the Open Rotor demonstration program, targeting to reduce fuel consumption and associated CO_2 emissions by 30% compared with current turbofans. Led by Safran (former Snecma), this program assembled a demonstrator in 2015 (see Figure 11), which performed the ground-testing in 2017 at the Istres site in southern France [43].

Figure 11. Open Rotor prototype by Safran.

In response, other companies, like Rolls-Royce, have also been resuming the work and progress from the 1980s ATP program to continue the development and testing on Open Rotor engines, recognizing a clear market opportunity for such technologies in the near future [44].

6. Is There a Future for Aircraft Propellers?

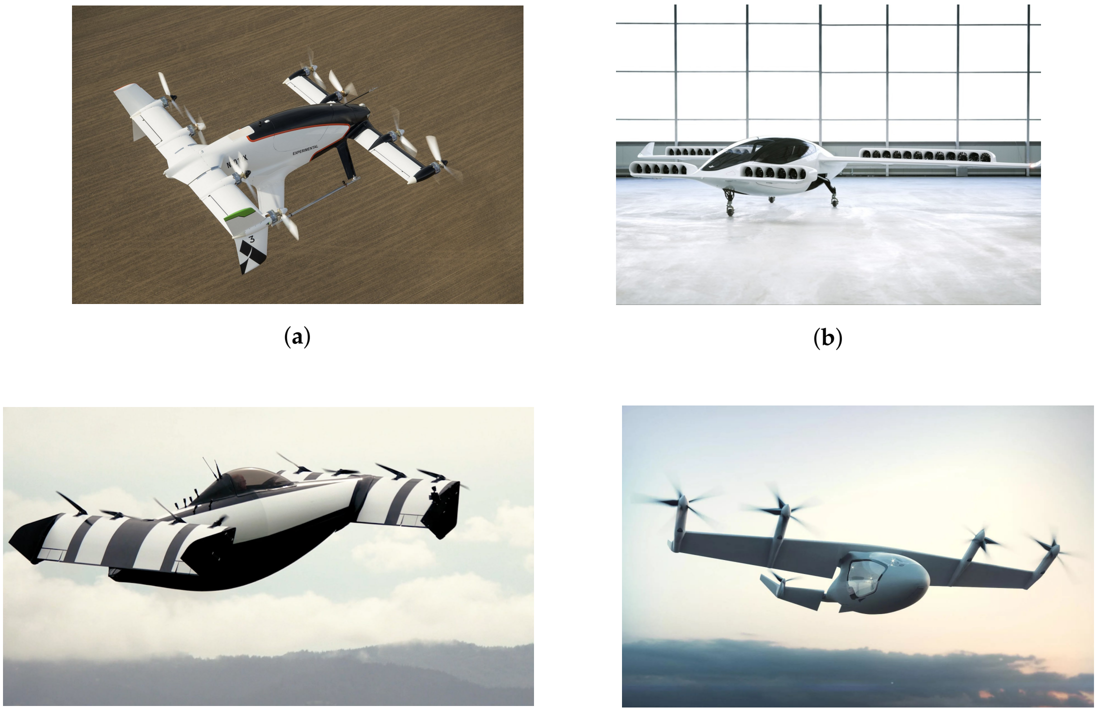
As seen in Section 3, on the one hand, the trend of increasing the bypass ratio in power-plants has been the way to increase the aircraft energetic and economic viability. It has ended up by introducing the gearbox turbofan (see Figure 5). On the other hand, the propeller (or propfan/open rotor fan) can be seen as an ultra-high bypass ratio propulsive device. The gearbox was perceived as a serious disadvantage that disappeared in relation to the recently introduced, geared turbofan. Nevertheless, other disadvantages concerning the use of propellers need to be addressed: higher noise levels and the maximum cruise speed limitation. In Section 4 is shown the acceptance in reducing the maximum cruise speed on consecutive turbofan airliners. On July 16, 2020, Israir, a fairly small Israeli airline with just seven planes in its fleet, including four Airbus A320 and three ATR 72-500, operated a flight from Tel Aviv to Kiev with one of its turboprop ATR 72-500 instead of the A320 (turbofan) [45]. Curiously, this route is stated at 1282 miles, considerably longer than the ATR 72-500 published range of 823 miles, which suggests a low flight load and velocity. The ATR 72-500 performed the flight in 4 h 55 min, while the A320 is capable of 3 h 25 min. Nevertheless, this shows that there are companies already willing to sacrifice flight speed by replacing turbofan aircraft with smaller, more economically viable, propeller-powered aircraft on considerably longer routes.

As stated in Section 5, since the 1970s, several factors were conditioning the broader use of propellers in the civil, commercial aircraft industry. However, the military never dropped the use of propeller aircraft. Their developments in the last decades, associated with current oil prices and ecology strategies, are re-introducing the turboprop aircraft in the civil market.

Finally, the recent developments in future hybrid and electric aircraft brought new challenges to the aircraft designer. When it comes to electric mobility, one of its most significant handicaps is the low energy density of current batteries. Although no disruptive progress is made in that area, the best approach to mitigate that obstacle is through better usage of the limited amount of energy that can be stored. This leads the design approaches back to propeller propulsive systems due to its, more efficient, ultra-high bypass ratios [46].

6.1. Multirotor Drone Emergence and the Future Personal Aerial Mobility

Multirotor drone emergence also re-introduced the propeller as the best-suited propulsion device for low-speed, low-cost, and accessible small aircraft. Furthermore, the enthusiasm for unmanned vehicles, alongside the broader access to technology, are accelerating the interest for personal aerial mobility and package delivery. The present reality of exploding numbers of electric multi rotary-wing drones is being followed by incorporating the fixed-wing flying mode into Vertical Take-off and Landing (VTOL) aircraft for range increase. It is likely that in the near future, electric VTOL (eVTOL) fixed-wing propeller aircraft will serve Uber-like personal mobility transportation systems. As a response to the rising thin-haul and on-demand transportation market, a growing number of startups, and more traditional companies like Airbus and Rolls-Royce are introducing smaller, mostly electric VTOL aircraft for urban air mobility applications. In [47], a review of the current technology and research in urban on-demand air mobility applications, including a comparison between 45 aircraft models, is presented. It is noticeable that in these categories, the propellers and jet propulsion still compete . However, the choice for the propeller-based propulsive systems is taking the lead. The higher efficiency that jet-powered ducted fans offer for high speed, high altitude cruise is not likely to be beneficial for urban applications, where lower speeds and altitudes are more common. In terms of safety, the usage of distributed propulsion is present in almost every new design, allowing improved propulsive efficiency and redundancy. The distributed propulsion takes advantage of typically smaller propellers, also reducing the overall noise with lower tip speeds. Figure 12 shows some of the relevant urban mobility contributions.



(**a**) (**b**) (**c**) (**d**)

Figure 12. Examples of VTOL aircraft demonstrator vehicles for personal transportation. (**a**) Airbus Vahana, by Airbus Urban Mobility. (**b**) Lilium Jet, by Lilium GmbH. (**c**) BlackFly, by Opener. (**d**) eVTOL, by Rolls-Royce.

7. Conclusions

Since the jet age, aircraft design aimed for speed and drove the airliners cruise speeds up to Mach 0.85. However, the 21st century brought a new sharp rise in energy prices [48], and consequently, a global economic crisis. At the same time, the global environmental consciousness is forcing the reduction of engine emissions, driving recent investigations to suggest that future airliners may have to reduce their design cruise Mach number [26]. Jet regional aircraft are, once again, becoming too expensive to operate, and the demand for turboprop engines rose again. Through the previous energetic crisis, the oil price has driven the progress and technological advance on propellers and their demise in favor of jets, feeding the race to fly higher and faster for decades. The race for speed reached its end, but the efforts to bring the propeller back to medium/long-haul airliners were abandoned as the oil prices dropped. Presently, the higher the oil price, the more likely the propeller comeback is becoming. The industry has played a more reactive than active role in this area. Nevertheless, beyond efficiency, propellers always offered benefits that the jet engine could not. Better take-off and landing performance allow transporting passengers to and from small regional airports. Also, its lower cost allowed enthusiasts and aviators to use them in their recreational, general aviation aircraft. In addition, the demand for turboprop aircraft increased due to a new wave of rising fuel prices, especially in countries that do not have a developed airfield infrastructure. At the very beginning of the 21st century, the propeller-driven airplane prevailed as a niche. However, this century brought new challenges and priorities. Recurrent oil crises are making propellers, and their specific advantages such as economic and environmental, the old answer to a prevailing problem. Therefore, propellers may have a role to play in progress again, even for commercial aviation. Nevertheless, the electric VTOL aircraft aimed for urban mobility seems like the new playground for propeller innovation. As noticed in the previous sections, the propeller has a future and we may be experiencing its rebirth in commercial aviation.

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Abbreviations

The following abbreviations are used in this manuscript:

ATP	Advanced Turboprop Project
CI	Cost Index
CPI	Consumer Price Index
EAG	Electric Aviation Group
ECAC	European Civil Aviation Conference
eVTOL	electric Vertical Take-off and Landing
IFR	Instruments Flight Rules
MMo	Mach Maximum Operating
MTOW	Maximum Take-off Weight
NASA	National Aeronautics and Space Administration
TSFC	Thrust Specific Fuel Consumption
VTOL	Vertical Take-off and Landing
WWI	World War I
WWII	World War II

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