PARE

PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

Perspectives for Aeronautical Research in Europe

2019 Report

CHAPTER 13

The Boeing MMA Prospects

Final Report

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Chapter 13 – The Boeing MMA Prospects

13.1 Introduction

The 'discovery' by Boeing, after half a century in the jet airliner market, that there's a special 'middle market' has motivated much controversy. The concept of Middle of the Market Aircraft (MMA) might not have won over scepticism without the weight of Boeing behind it. Boeing can be rather inventive, for example with the 'sonic cruiser' that was an engineering marvel airlines would willingly discard in favour of the cost-efficiency of the more conventional 787. Similarly, could the MMA simply give way to the 737 replacement that is badly needed and could not come too soon? To rise above the speculation three aspects need to be considered:

- Is there a 'Middle Market' (MM) single and twin-aisle (SA/TA)?
- If so, which aircraft serve the MM and what does that tell about a potential replacement?
- Could an MMA be combined with a B737 replacement or have comparable appeal?

13.1.1 Between Single/Twin-aisle (SA/TA)

The current airliner market could be seen as a mostly bi-modal distribution:

- The single-aisle (SA) with up to 200 seats cover transcontinental routes;
- The twin-aisle (TA) aircraft with well over 200 seats cover transoceanic ranges (over land or water).

Certainly, there is a less densely populated middle ground of 200-300 seats and transatlantic and/or transpacific ranges, and some past aircraft well-tailored to such routes with Boeing heritage: the B757 and B 767.

A closer examination of that middle of the market shows that the B757/B767 are less than 20% of the fleet, hardly surprising in view of their age. The SA aircraft did not have (until recently) the necessary payload-range, so the middle market is dominated to an extent of over 80% by TA aircraft like the B787, A330 and A350. They were optimised for larger capacities over longer distances but they were until recently the only choice for the middle market. In this scenario, the MMA could be more efficient than the TA aircraft, but it would cannibalise their sales. The lost sales of TA aircraft and the limited middle market might not justify the development costs.

The preceding assessment does not take into account a major new development. When the Airbus A320 and the Boeing 737 were designed they were never expected to cross the Atlantic. The new generation of engines adds to the benefits of lower fuel consumption those of longer range. The A320 family in its second generation has greater development potential that the B737 in its third generation and Airbus is not missing the opportunity. Most of its sales advantage comes from the longer-range A321 and A321LR, and with the A321XLR and possible further growth the B757/B767 replacement market is squeezed from below and by the A330 neo from above, Even if the A330neo is no more than a lower cost less efficient alternative to the B787, little room is left below it for the MMA.

13.1.2 Technological Advances for the MMA

The MMA should incorporate all the technological advances planned for all the new clean sheet B737 replacement later in the decades before the third generation 737 MAX becomes a case of urgent necessity rather than favourite choice and certainly, airlines will be always eager for greater efficiency allowed by a new design. However, just after the introduction of new engines, still suffering from early teething troubles, not much more efficiency can be expected anytime soon. Without a major contribution from the engine will other areas (aerodynamics, structures, new production methods, big data, artificial intelligence, operations) make enough difference?

Also, most airlines have a two-type fleet: single (SA) and twin (TA) aisle. Does it make sense having a third type: MMA? Even if the MMA is better optimised for middle-market routes does it justify operating another type, different spare parts and maintenance organisation and specific crew training? Probably not unless it shares an extensive commonality with a SA aircraft. It is not surprising that Boeing presents the MMA as a “family of aircraft” that will eventually include a B737 replacement.

This begs the question of what is really the main aim: a badly needed B737 replacement or an MMA with an uncertain business case? Or does the combination add much value? There is also the argument of which comes first: (a) the MMA as the technology pathfinder for a mature fast development of a B737 replacement? (b) or the urgently needed B737 replacement with the MMA a follow-on option to consider. As times elapses without an MMA decision option (b) gains weight for several reasons.

13.1.3 The need for a B737 replacement

The B737 replacement is the aircraft that Boeing wants for all sorts of reasons: (i) because it is the clean sheet design it has been working for years before the 373 MAX diversion; (ii) because the third generation 737 MAX is at the limits of the development potential of a design half a century old; (iii) because it is competing with the second generation A320 and a gap of one generation is almost impossible to bridge; (iv) although the 4 500 orders of the B737 MAX are a respectable result for a late entry against 6 500 orders for the A320neo, the gap is mostly due to the A321/LR/XLR that lies beyond the B737 stretch potential.

The MMA may no more than a smokescreen behind which Boeing completes the development of an all-new B737 replacement. Boeing cannot admit that the B737 has reached the limits of its development potential. It needs to develop an all-new aircraft without fatally undermining the current model. Maturing the new technologies in the MMA and applying them in the fast and successful development of an all-new B737 replacement might be the best course of action, with sufficient time.

The B737 backlog of several years gives Boeing some time to develop its replacement but not enough to put an eventual MMA ahead. The B737 replacement could be the first priority. The recent troubles of the B737 MAX will drain Boeing resources as its highest priority, but once this is over the all-new replacement must be the overriding objective, to compete with the A321 derivatives and erase B737 MAX bad memories. In the meantime, Airbus can push the A321 from below and A330 from above and when it sees fit, counter the B737 replacement with an A320 replacement benefiting from hindsight. The Boeing hesitations and postponements of the MMA are a sign of troubled times and difficult options.

13.2 KEY TOPIC T13.1 – What if Study 2: Boeing MMA Aircraft

Executive Summary

In the last 40 years, the aeronautical industry has managed to move from a specialized sector to a worldwide leading industry. Prospects for the growth of this sector are optimistic. Main aircraft manufacturers, like Boeing, Airbus, Bombardier, etc., foresee an increase in the air travel demand per year for the next 20 years. Despite the positive perspective for the market, many challenges populate the road towards this upcoming future. To succeed, the aeronautical industry must keep innovation as one of its main assets. Breakthrough and emerging technologies will continue to be the main development differentiator, and sustained efforts in R&D are essential to ensure sustainable growth. Strategic responses are being prepared by governments and international institutions.

Within these international efforts to cope with these challenges is where PARE comes along. The overall objective of PARE (Perspectives for the Aeronautical Research in Europe) is to trigger collaboration between European stakeholders to support the achievement of the 23 Flightpath 2050 goals. As part of this process, the project has the task of identifying the actions required in the coming future for the proper development of the aerospace research sector, that can benefit from a detailed and rigorous analysis of possible political, social and industrial scenarios by carrying out, among other works, some "What if "analysis. "What if" study follows a double methodology. On the one hand, a qualitative and analytical approach typical of market and competition studies. Additionally, the "what if" analysis is complemented with the application of game theory to evaluate the results of the possible competition strategies.

The "What if" case studied in this text addresses the competition among the main aircraft manufacturers in a segment that has captured the attention of both in recent years, the Middle of the Market, MoM. It represents the airliner market between the narrow-body and the wide-body aircraft as well as between the short and the long-range. These aircraft can fly ranges of approximately 3,000 to 5,500 nm and carry passenger loads of approximately 180 to 300 people in both single and twin-aisle configurations. The MoM is not currently clearly defined, it is broad, and its boundaries are very blurred, as MoM routes sometimes can be covered by both narrow-body and wide-body, and operators use indistinctively these two types. This study has followed a data-driven approach to shed light on the definition of the MoM by analysing aircraft models and market share from 2018 flights data provided by Open Flights web page.

For the purpose of MoM sector analysis, routes are classified as: a) Short-haul: Routes no longer than 2,500 nm; b) Medium-haul: Routes between 2,500 and 4,500 nm; and c) Long-haul: Those routes longer than 4,500 nm. The medium-haul traffic is the target of the future Middle of the Market Aircraft (NMA) production, and it represents about 20% of the total worldwide traffic. Nowadays, the biggest number of scheduled mid-haul flights still corresponds to pairs between North American and European cities, with over 30% of the volume of routes in total. There is also a big number of routes within China and Europe with 6% of the routes, and within Europe and South/Central America, with Spain as the hub of these connections. Additionally, an important market exists in the air routes crossing the Pacific Ocean and connecting countries like Japan and the US. The rest of the flows are very varied and each of them represents less than 5% of the total number of routes.

Today, there is not an aircraft model designed and optimised for these routes, so that several aircraft types absorb part of the MoM market share in different magnitudes. Figure A shows the aircraft that are currently operating in MoM routes. Figure B presents the current market share of the MoM.

Figure A. Current MoM aircraft

The 98% of MoM market share corresponds to Airbus and Boeing models. Today, MoM is dominated by models with very high ranges. Wide-body aircraft such as the A330, B787, and B777 possess a significant market share, reaching between the three families a market share of 70%. Several models used for these routes are old versions which have been in the market for a long time. This is the case of the A330-200/300, B777-200/200ER and B777-300/300ER variants whose replacement is expected with new variants such as the A330neo which has just entered the market and the B777X of which introduction is planned around 2020. The A320 and B737 families absorb together 4% of the market share. Some models used for these routes are previous versions such as the B737 Next Generation and A320ceo families, whose range is lower compared to the most modern versions. It is very likely that this percentage will increase when new variants such as the A321neoLR and B737 MAX 8 remain several years in the market and fly a higher number of routes. Other aircraft even larger, such as the A350, A340, B747 or A380 are also used for these routes, although in a much smaller proportion. It is expected that their market share will be absorbed by the A350, a more recent aircraft with similar range and capacity capabilities and less fuel consumption. Finally, the B757/B767 fleet represents 10% of the market share. However, these models are no longer in production and they are expected to be retired in the upcoming years.

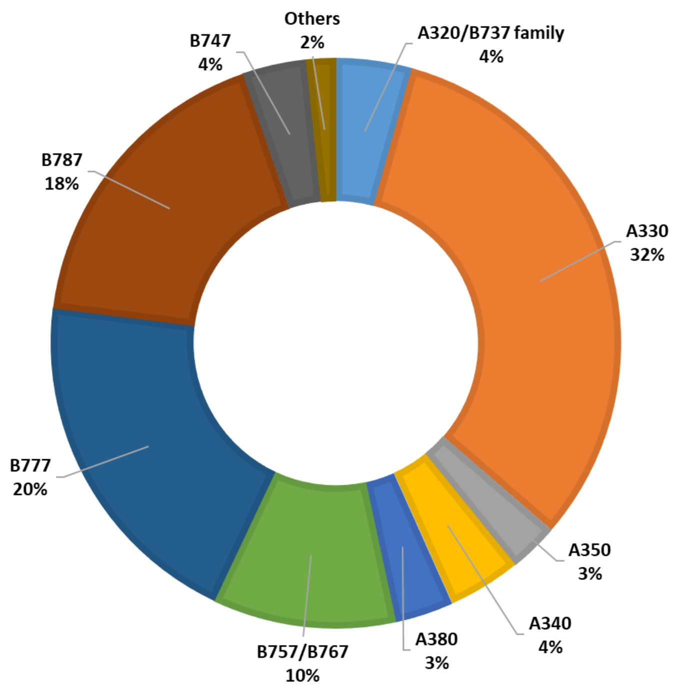


Figure B. Market share in medium-haul routes in 2018

To forecast the number of airplanes demanded by airlines and passengers in the future, five different worldwide studies covering a forecast period of 20 years as well as global passenger fleet has been used in this report. Main conclusions extracted are shown in Table A.

Publisher	*Air Traffic Growth p.a.*	*Fleet count 2018*	*Fleet 2037 Forecast*	*Deliveries*	*Main hypothesis and considerations*
Airbus *Global Market Forecast 2018-2037*	**4.5%**	**19,803**	**46,121** ***(x 2.3)***	**37,419**	• Wealth effect. Middle class growth stimulates traffic growth. • Low-cost business models are the main drivers of the future market
Boeing Commercial Market Outlook 2018-2037 Co	**4.7%**	**24,400**	**48,540** ***(x 1.9)***	**42,730**	• GDP growth leads to more consumer spending that involves air travel • New liberalized policies (open skies agreements) will stimulate air travel • Airport congestion • Arise of low-cost long-haul business models

UAC United Aircraft Corporation (UAC) Market Outlook 2017-2036	**4.6%**	**26,500**	**52,400** ***(x2.0)***	**43,659**	• China and Asia-Pacific region as the main drivers of the sector
JADC JADC Worldwide Market Forecast 2018-2017	**4.5%**	**26,463**	**48,900** ***(x1.8)***	**33,530**	• Slight increment on crude oil prices • Increase of the worldwide middle-class and tourism • GDP growing lead by China
Airline Monitor Commercial Aircraft Market Forecast 2017 – 2040	**5.1%**	**26,042**	**52,578** ***(x2.0)***	**46,190**	• Air transport growth directly linked to GDP growth (with an elasticity of 2.5 approx.)

Table A. Forecasts' results and hypothesis summary

From these hypotheses, a specific forecast for the MoM has been constructed. MoM fleet will be 2.5 times bigger in 2040 than what it was in 2018. Asian airlines (which include those from Middle-East and Asia-Pacific regions) will account around 50% of the total mid-haul fleet, whereas Europe and North America will decrease their share of the total fleet from 50% in 2018 to 37% in 2040, as a result of the accelerated growth from the emerging countries. More than 2500 aircraft belonging to the MoM sector will be retired worldwide, and the global market will account more than 8400 deliveries in the forecast period. The results of the forecast are presented in Table B, differentiating by region. The Asia-Pacific region together with the Middle East will account more than 60% of the deliveries within this market, whereas Europe and North America will receive a third of the total new-built aircraft. A total of 588 aircraft will be retired in Europe within the MoM and 520 in North America, which means 59% of the 2018 fleet, will have to be replaced in both cases. Nearly 80% of the 2018 MoM fleet will be replaced by 2040 in Asia-Pacific, and about 90% in the Middle East. 73% and 76% of the deliveries will expand the fleet of the Asia-Pacific and Middle Eastern airlines, respectively. In Europe and North America, these fractions are of 60% and 57% respectively.

Region	MoM fleet 2018	MoM fleet 2040 (growth)	MoM Retirements	MoM Deliveries (% of total)
Asia-Pacific	791	2401 (x3.0)	612	2257 (27%)
North America	882	1625 (x1.8)	520	1286 (15%)
Middle East	592	2237 (x3.8)	528	2205 (26%)
Europe	993	1877 (x1.9)	588	1497 (18%)
Latin America	179	545 (x3.0)	139	513 (6%)

Region	MoM fleet 2018	MoM fleet 2040 (growth)	MoM Retirements	MoM Deliveries (% of total)
Africa	159	446 (x2.8)	119	413 (5%)
CIS	176	366 (x2.1)	110	305 (3%)
World	**3772**	**9497 (x2.5)**	**2615**	**8476**

Table B. MoM Fleet, retirements and deliveries by region

The main key driving forces influencing the evolution of air traffic, airplane production and evolution of the Middle of the Market segment have been analysed: i) Fleet obsolescence and retirement; ii) Doubling the traditional 7 years' jetliner growth cycle; iii) Replacement of B757; iv) Replacement of the B767; v) Interactions in the Markets for Narrow and Wide-body Commercial Aircraft; vi) Fuel prices evolution; vii) Fuel efficiency evolution; viii) Technologies to improve fuel efficiency, others than engines; ix) Environment regulations; x) Manufacturer Subsidies; xi) China market evolution; xii) Low-cost operation in the MoM; and xiii) Airport congestion increase.

Additionally, key success factors for a new Middle of the Market Aircraft (NMA) have been identified and discussed, in particular, the expectations of airlines, the production rate and the feasibility of new engines for a new clean-sheet design aircraft for this market. Since the commissioning date of a new aircraft is scheduled for 2025, the possibilities of engine manufacturers to create and develop new engine architectures are limited. In this aspect, the use of current gas generators (cores) of the engine with their subsequent improvement, as a thermodynamic machine, is most appropriate. However, achieving the necessary reduction in fuel consumption in this way can be difficult and costly. It is possible to achieve a significant increase in fuel efficiency by a combined method, namely by an increase of bypass ratio, the use of a geared fan and an increase in engine operating cycle parameters. Three main potential engine manufacturers have been considered: Rolls Royce, CFM International and Pratt and Whitney. All of them have the technology and potential to develop a new engine for a Boeing NMA within a specified timeframe. All three considered companies use similar directions to improve power plants based on improving the aerodynamics of the air-gas channel of the engine and its nacelle, the use of ceramic composite materials for combustion chambers and turbines, the use of new alloys for compressors and other engine elements. This is determined by the desire to improve the weight perfection of the engine, to increase the parameters of the operating cycle, to reduce losses in the engine, etc. A significant difference is the use of a geared fan in the PW 1000G engine family.

To complete the market and competition approach, an economic valuation program has been developed to estimate the payoffs for the manufacturer's strategies under different scenarios and varying market conditions. The purpose is calculating the profits of airliners in terms of Net Present Value derived for the future sells of current models as well as re-engineered models or new cleans designs. The economic valuation models consider all the aspects identified in Figure C.

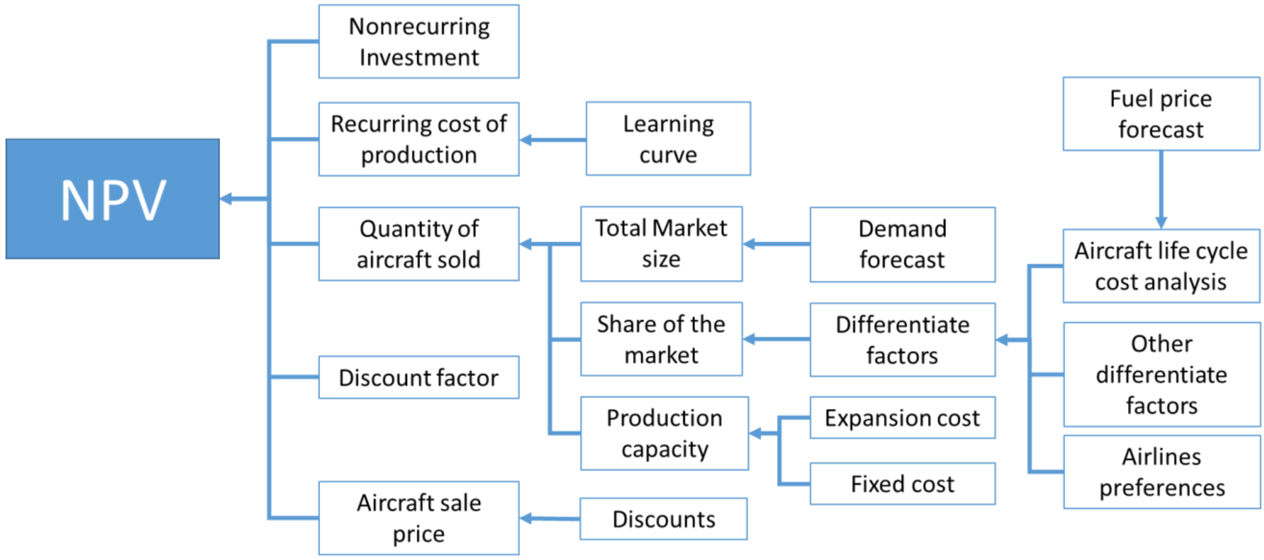


Figure C. Model program cost methodology

Figure D. SWOT analysis for the new MoM aircraft

All the previous elements are synthesised in a SWOT for the Boeing NMA as in Figure D and have been used to analyse Airbus and Boeing possible competitive strategies in the MoM. Those strategies have been finally tested trough Game Theory analysis.

Historically, Boeing dominated the medium-size aircraft market. The Boeing 757 and 767 lead this segment offering variants that span from the 200 seats of the B757-200 to the 296 seats of the B767-400, offering ranges that varied from 3,300 nm to 6,590 depending on the version. In recent years, Airbus has reached a strong position within the MoM with models such as the A321neo or the A330, overcoming Boeing in orders and gaining market share. Currently, Boeing's offer in the MoM market segment is the Boeing 737 MAX 8, which belongs to the next generation 737 MAX narrow-body family. However, the A321neo, which is the main rival of the 737 MAX 8, has achieved great success from customers, getting really good sales thanks to its performance advantages, in terms of operating and unit costs.

With Boeing's market share in the MoM segment declining and Airbus share increasing, Boeing has to take some action to change this situation. The main option that Boeing is considering is the new MMA aircraft, although others have been considered. Boeing's best-sellers 737 and 787 hold a respectable share of the lower- and upper- layers of the Middle of the Market, respectively. The Boeing 737 MAX 8 and 9 operate many of the routes between 2500 to 3000 nm, and the 787 holds more than the 30% of the MoM routes nowadays. These products aim to compete with the A321 LR and XLR variants, but each of them is designed for a different mission, which makes them less flexible than the Airbus competitor. Boeing has been proposing different options to modify these aircraft, but none seems to be competitive enough to save Boeing market position in the MoM.

The scenarios of a potential Airbus response to Boeing's NMA have been discussed, including options like extending its current product line by stretching the current models, the impact of the long-range variants of the A321neo, or the possibility of developing a new Airbus mid-size aircraft.

The analysis shows that the most promising Airbus strategy is the evolution of the Airbus 321LR that could absorb an important chunk of the market before Boeing decides to launch any new mid-size aircraft programme. A321LR can be re-engineered, resulting in the Airbus A321XLR with 4700 nm of extended range, higher MTOW, strengthened landing gear and reinforced fuselage structures, several weight-saving modifications, as well increasing fuel capacity while maintaining the same wing.

The strategies of both manufacturers are synthesized in Figure E. The payoffs each manufacturer will obtain in each case are illustrated in Table C. All together constitute a strategic game analysis. A strategic game reflects a situation where two or more participants are faced with choices of action. The choices of action may imply gains or losses for each participant, depending on what the others choose to do or not to do. Therefore, the final outcome of the game is not determined by the strategies or actions of a single participant, but instead, it is the result of the combination and interaction of the strategies applied by all the participants.

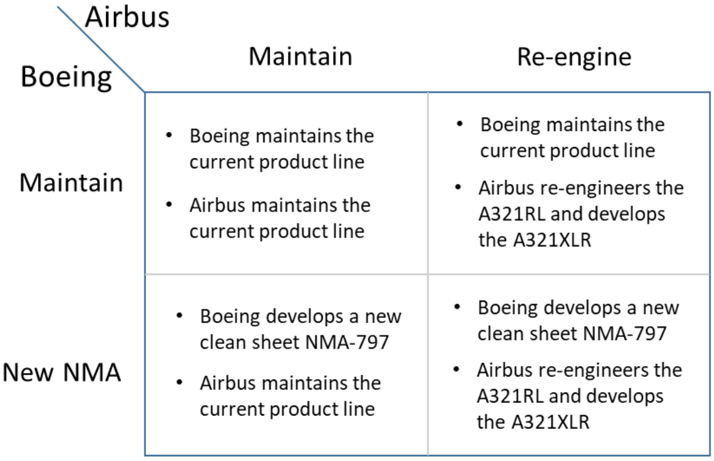


Figure E. Reference scenario possibly strategies

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	Payoffs: B: 62.257– A: 74.810 MoM Market share B:45%, A: 55%	Payoffs: B:44.326—A: 93.405 MoM Market share B: 37%, A: 63%
Launch NMA	Payoffs: B: 56.192 – A: 46.488 MoM Market share B: 61%, A:39%	Payoffs: B: 49.724 – A: 54.248 MoM Market share B:55%, A 45%:

Table C. Reference scenario payoffs and MoM market share

In the analysis of this strategic competition, fuel efficiency and aircraft operating costs are the key drivers for airlines buying decisions. The forces governing market share favour the aircraft models that implement latest fuel efficiency technology, improved engines, lower weight and in general reduced operating cost. In this scenario, manufacturers share incentives to innovate and to propose re-engineered versions of current fleets or new clean sheet designs. Additionally, gains in efficiency will justify that manufacturers might increase the selling price of new models, as far as they are offering features and significant performance improvements to justify price increase through the aircraft lifespan.

Game analysis of this situation concludes that the situation of equilibrium corresponds to the situation in which Boeing takes the decision of developing a new clean-sheet aircraft model, the B797, which would enter in service by 2025. On the other hand, Airbus takes the decision of extending the A321LR range capabilities, resulting in a re-engined version called A321XLR. This decision would be taken in 2020 but the new A321XLR program would not enter service before 2025. In this scenario, Boeing could maintain its leadership position in the MoM, however, due to the high investment required to its development, the NPV values obtained are very similar to Airbus benefits.

These results have been subject to a sensitivity analysis by examining the impact in the final equilibrium of external conditions through the following scenarios: a) Expectation of Low Fuel Prices; b) Technology Forcing Regulations; c) Manufacturer Subsidies, d) Expectation of High Fuel Prices, e) Increase in Airport Congestion; and f) Development of low-cost carriers in the MoM sector.

Each of these scenarios influences the payoff each company may obtain but it does not modify the equilibrium situation, except for the case of low fuel prices. In this scenario, fuel efficiency is not the main driving force of the market and bigger aircraft are more prone to gain market share. In this case, the equilibrium would recommend Airbus to invest in the A321XLR. However, the best option for Boeing would be not to develop the NMA, because the higher cost of developing a new clean sheet aircraft will not be re-compensated by a significant improvement of its market share.

Additionally, a dynamic game has also been performed to confirm the best timing for the decisions. Committing to a re-engined or new aircraft locks into a technology level for 10 or more years requires an investment and can be risky. Delaying the decision provides more flexibility for future actions but gives competitors an opportunity to develop a superior aircraft earlier, access first to the market and gain a significant share of the market in the intermediate period.

"What if" study recommendations

Recommendation 1. New aircraft product lines should capture better the airlines' needs in term of seats and range and should provide the flexibility required by new operation modes the airlines will have to define to answer travel demand.

- **Rationale:** New aircraft market classification redefines the traditional distinction between single-aisle or narrow-body jets and double-aisle or wide-body jets, and between the various types of long-haul aircraft.

Market segments have evolved during the last years in terms of range and number of seats. The size is increasing with a clear overlap between segments, reflecting a blurring of the boundaries between market segments. Today, for example, larger single-aisle types like the A321 operate in what would have been considered a twin-aisle market space. This is not just true for single-aisle types; larger aircraft like the A350 can operate in a number of segments depending on airlines or market requirements.

New classifications reflect the way in which airlines use their airplanes independently of the type of model. The new statistical framework does not take into account the number of engines and focuses on the segments by the number of seats, reflecting the opinion that long-term forecasts do not have to coincide with current product lines.

- **Justification**: What if analysis 1: "The MMA case", section 13.2.2.1.

Recommendation 2. The maximization of single-aisle range, while maintaining reduced CASM (Cost per Available Seat Mile), will give manufacturers a substantial competitive advantage to compete in the MoM.

- **Rationale:** In an extremely competitive air transport environment, CASM (Cost per Available Seat Mile) is becoming more than never the criteria that guide airlines fleet decision. The new generation of single-aisles A320 neo and B737 Max, have achieved excellent records in CASM, and at the same time have enlarged the aircraft range, improving economic results of longer routes.

Smaller operating cost gives a single-aisle aircraft a competitive advantage in the MoM and making them the favourite of airlines. The maximum capacity of these aircraft is around 240 seats in 1-class configuration and with 28" pitch. The new engine improvements on the new models such as the A321neo LR with lower fuel consumption have allowed these single-aisle aircraft to cross the Atlantic offering a 27% lower fuel consumption than the previous generation's Boeing 757. One of the advantages of flying small airliners is that it is not necessary to have a very high occupation factor to make a profit out of it. On the other hand, the comfortability is limited due to the limited space. The strategy of airlines nowadays is offering flights with a lower number of available seats but increasing also the frequency. Thus, flying is profitable, allows flexibility of scheduling and satisfies the passengers' demand.

Big wide-body jets are usually more comfortable and the favoured ones of the customers due to the higher pitch and the bigger size of the seats. Operating these aircraft in short-haul flights is not impossible but difficult. For a flight to be profitable, it is necessary to sell a high percentage of the tickets, since the fuel consumption per seat ratio is bigger than in narrow-body aircraft. On the other hand, bigger jets allow flexibility in airport operations since the number of flights is reduced, which can be a medium- or long-term solution to avoid airport congestion.

- **Justification**: What if analysis 1: "The MMA case", section 13.2.2.2.

Recommendation 3. Data-driven analysis should become standard practices in any research study about future air transport and airliners prospects. The development of an adequate open and accessible data framework, that allows analysing real data reflecting how airplanes are effectively used and operated by airlines worldwide, is essential for an informed decision-making process.

- **Rationale:** Research studies about future air transport and airliners prospects need to complement theoretical performance information provided by manufacturers with as much as possible real data reflecting how airplanes are effectively used and operated by airlines worldwide. A data-driven approach is essential to support informed decision-making process. However, data required for this type of analyses are sometimes not publically available, or only partially accessible through different not interconnected databases without quality assurance guarantee.

- **Justification**: What if analysis 1: "The MMA case", section 13.2.2.3.

Recommendation 4. New routes and market opening should be carefully watched in the coming years to improve current estimates for the potential growth of the MoM.

- **Rationale:** The MoM fleet will experience significant changes in the next years. There is not an aircraft model designed and optimised for these routes so that several aircraft types absorb part of the MoM market share in different magnitudes. Certain aircraft models have just entered the market or are expected to enter service in the following years. Models such as the A330neo or B737 MAX are very recent, and they hardly have routes nowadays but it is expected that this situation will change in the near future. It will be also necessary to consider fleet retirement since several of the aircraft currently operating this range are old versions and it is very likely that some of them will not be longer in production in the next 20 years.

- **Justification**: What if analysis 1: "The MMA case", section 13.2.2.4.

Recommendation 5. A framework of institutional and industrial measures that counterbalance the higher risk of developing new clean-sheet design wide bodies might benefit the innovation in the Middle of the market.

- **Rationale:** Today MoM routes are mainly operated by wide bodies, although it is expected that this might change in the future. Both manufacturers are pushing to extend the market of their current single-aisle bestseller products, by improving its engines and stretching the airplane. In today's aerospace market, the MAX and the Neo are the best-selling products for both manufacturers. These models are more fuel-efficient, longer-ranged, enhanced passenger interior and enhanced passenger comfort than previous B737/A320 families, both of which have sold very well since their introductions.

Companies might perceive wide-bodies as riskier. The current wide-body fleets do not record any model numbering over 2,000. The WB BB ratio (book-to-bill ratio) is less than 0.5 for Airbus while for Boeing is a little better, close but still under 1. A BB less than one might signal a certain reluctance of the airlines to commit to higher capacities. Wide bodies also imply a higher risk for manufacturers in term of complexity, cost and smaller market.

Higher risks in WB development together with the attractiveness of increased return to adoption for bestseller single-aisle might preclude innovation in the middle of the market. A new framework of institutional and industrial measures that counterbalance these negative effects might benefit innovation in the Middle of the market.

- **Justification**: What if analysis 1: "The MMA case", section 13.2.2.4 and chapter 13.2.3.

Recommendation 6. Substitution of B757 and 767 will be a key window of opportunity in the MoM. To catch the potential of the retirement of these fleets, manufacturers cannot delay their decisions for the MoM further than 2020.

Recommendation 7. The company that will offer the sooner alternative substitution solution for B757 and B767 fleets will benefit from initial higher market shares in the MoM.

- **Rationale:** Over the past decades, the world fleet of aircraft has slowly increased to more than 27,000 commercial aircraft operating worldwide, with an average age of about 13 years. As a result of the growing world fleet and lower average age, there will be an increasing number of aircraft removed from service and subsequently decommissioned in the upcoming years. Several models of aircraft which operate the MoM are aged and, as a consequence, many retirements, 40% of the MoM fleet, are expected in the following years. Therefore, fleet obsolescence must be taken into account in this study, especially the case of the B757/B767 fleet. B757/B767 fleet represents 10% of the MoM share. However, these models are no longer in production and they are expected to be retired in the upcoming years.

Getting to market earlier means that the company will have more opportunities to dominate a particular market segment before a competitor can react. If a company can lock in more customers, it has a better chance of both producing more units and smoothing the production run over the product's life cycle and thereby realizing its learning economies. By getting to market faster, the forecast for the product and the expected profitability of the program are more likely to be realized.

- **Justification**: What if analysis 1: "The MMA case", section 13.2.2.4, section 13.2.6.1, and chapter 13.2.3 and Chapter 13.2.4

Recommendation 8. The expected growth of the MoM will require manufacturers to speed up and maximize opportunities to bring into their structure new engineering and production resources, for example by acquiring/merging other firms.

- **Rationale:** For example, Boeing industrial production capacity is quite stretched by their huge efforts to ramp-up production for the existing types and to introduce the new 777X. A need to extend the production capacity to accommodate MoM aircraft might occur after 5-6 years when the production levels are, hopefully, stabilised. Boeing engineering capacity is also compromised. Company resources are involved in 777X and they will not be available for other jobs before 2020. In this scenario of restriction, the Embraer merging might bring not only a new market extension but also new required engineering resources.
- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.3.

Recommendation 9. Customer-oriented strategies will be a key factor to reach success in the MoM. The company that can consistently and efficiently do all of these will be the winner at the end.

- **Rationale:** Both Boeing and Airbus carefully research customer needs and strive to satisfy these needs since they represent a competitive and successful factor for a company. In addition, the airplane purchasing decision criteria of airlines includes not only load and range factors and operating costs but also passenger comfort. Airbus has been quite competitive and successful in recent years as a result of developing a clear empathy with its customers, encouraging a two-way flow of views, ideas and technical feedback on its aircraft in service around the world. At present, Boeing and Airbus appear equally competitive. Both companies must understand their customer's needs and buying behaviour, anticipate how customers' needs will evolve over time, keep a close eye on the competition, be innovative in creating customer value, and strive to deliver total customer satisfaction. Clients in the MoM have different types of requirements. The big three U.S. carriers which are potential B797 buyers and their counterparts across the Pacific have very different views on how much baggage and freight the airliners should haul, what might affect greatly the aircraft design features.
- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.3 and 13.2.11.

Recommendation 10: Quantifying adequately the size and needs an evolution of the MoM will be key for airliners strategies for the next years.

Rationale: The medium-haul traffic represents today about 20% of the total worldwide traffic, and a big number of the aircraft to be produced will be used to operate in this market. This volume is equivalent to the expected Chinese market by 2037. The segment is not clearly defined, and a broad variety of models operate in these routes currently. Because of the average age of the aircraft operating in this segment, important movements could take place in the next 20 years.

When a new MoM aircraft would be entering this market, after 2025, the market will not be the same as today. The market will have grown by 100 million passengers in Asia alone and present aircraft will not be large enough to handle this growth. In addition, there is a large replacement market. Up to 40% of the market value is destined to the replacement of existing aircraft in this category, which is less suited for the job.

Aircraft are chosen by airlines to cover the routes they want to fly. Nevertheless, the opposite situation happens too. Over the last few years, aircraft with new capabilities opened some 400 new routes that existing aircraft could not do because they did not have the economics. This will create a new fragmentation of the market. A good example of new routes opened thanks to new aircraft introduction is the new generation of long-range aircraft such as the Boeing 787 and the Airbus A350, which were able to open the longest routes ever seen in the market.

- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.3, 13.2.4 and 13.2.6.

Recommendation 11: Solving constrains and saturation in air transport infrastructures and supporting ATM services should be a priority worldwide.

- **Rationale**: From the published air traffic and aircraft demand forecast, it can be concluded that Boeing believes in an increase of the average aircraft size in the future. This assumption is present on the forecast's results since, despite predicting more optimistically the air traffic growth per year (4.7%) than Airbus (4.5%), the future fleet is forecast to be 1.9 times the actual one, as opposed to the 2.3 times multiplier of Airbus' forecast. This shows that Airbus believes in a dominance of the single-aisle segment as it has been occurring the previous years, representing more than half of the deliveries worldwide. On the other hand, Boeing believes in an increase of the wide-body aircraft demand, motivated by the infrastructural constrain and airport saturation. Air transport infrastructures and supporting ATM services constrain and saturation might highly impact the development of MoM routes in the next 20 years.

- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.6.

Recommendation 12: From parts distribution to dismantling, through materials recycling, aerospace leaders should develop new strategies and processes for management of end-of-life aircraft.

- **Rationale:** With an estimated 12,000 aircraft retiring in the next two decades, aircraft recycling will bring new problems and responsibilities, but also a broad range of opportunities for expanding the aerospace business. Aircraft's components should and could be safely dismantled and recycled for reuse in the aviation or other sectors. As the international aerospace community continues to focus on environmental issues and landfill regulations mount, asset owners will need to look for efficient, revenue-building and environmentally-sound methods for aircraft disposal.

- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.6.

Recommendation 13: Long term impact of the usual seven-year cyclicality duplication pattern in jetliner manufacturing needs to be carefully considered from a sustainability perspective.

- **Rationale:** The extended growth cycle experienced by the industry, with continuous growth since 2004, is imposing severe growth requirements on all the supply chain. For the very first time, the jetliner market will have a 16-year growth cycle, and possibly longer, over twice as long as the usual seven-year boom.

- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.6.

Recommendation 14: The analysis of the Middle of the Market segment will extend the state of the art of competitive analysis because it implies the analysis of a segment that can be covered by several models of each manufacturer.

- **Rationale**: Both companies, Airbus and Boeing, have completed product lines that span all 100+ seat market segments. Decisions within one market segment are constrained by the state of products in other market segments. In the past, limited capital and engineering resources have prevented manufacturers from undertaking more than one major aircraft design program at any one time.

Conventional studies have neglected this complexity by assuming that manufacturers decide on the single-aisle market without constraints imposed by the decision regarding the twin-aisle market. The competitive structure of the market for wide-body commercial passenger aircraft has been extensively explored by the literature because the market features several interesting analytic properties such as learning-by-doing, differentiated products, and active trade policy. Fewer studies have tackled the narrow-body market, much more complex and with much more actors.

For a proper analysis of the MoM, it could be necessary to consider multimarket oligopoly models. When considering the purchase of an airplane, airlines can choose to either buy a single, large plane to fly fewer routes or buy multiple small planes which will run more frequently. This decision suggests that wide and narrow-body planes have strong interrelated demands. If a firm operates in two markets, a change in one market can affect the outcomes of the other market by changing competitors' strategic choices and by changing the firm's own marginal costs. Therefore, to understand better the commercial aircraft industry as a whole it is necessary to explicitly study the wide and narrow-body markets together.

- **Justification**: What if analysis 1: "The MMA case", chapter 13.2.6.

Recommendation 15: Main emphases need to be done in the coming years on technologies to improve fuel efficiency, others than engines.

- **Rationale**: Reducing fuel consumption on modern aircraft can be achieved by investigation and implementation of new technologies into production. The range of research being conducted is quite wide. All aircraft systems are subject to improvements. Engineers and scientists are continuously struggling to reduce the weight of the structure, increasing the wing lift, while reducing the final weight of each aircraft system as well as maintaining its fail-operational capability and reliability. This concerns not only the systems which allow aircraft operation, take-off or landing, but also the systems providing passenger comfort and commercial attraction of the flight as a whole.

In addition, ecologists are concerned about the increase in the share of emissions from commercial aircraft; this is another incentive for the development of fuel-saving technologies. Furthermore, new ICAO standards for permitted noise levels of the aircraft, whose take-off weight exceeds 55 tons, came into operation on December 31, 2017. This is an additional incentive for aircraft manufacturers, pushing them to introduce and develop technologies that reduce fuel consumption by aircraft engines since the level of noise produced directly depends on the amount of fuel consumed.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.6.

Recommendation 16: MoM aircraft should look carefully to the needs and requirements of LCC for medium-haul routes.

- **Rationale**: The share of the LCCs in the Middle of the Market is expected to reach around 30-35% in the following years.

The number of connections made by LCCs is continuously increasing, especially due to the extended use of secondary airports as airline HUBs, due to the lower fares. In the Middle of the Market, the number of routes offered by the LCCs is around 11% of the total market. Europe and North America are the regions more connected by these types of carriers, followed by Asia-Pacific countries. Europe and Latin America are also starting to be connected by LCCs as the liberalization of the Spanish-Latin American air travel begins.

Considering the totality of operations, the share of LCCs against traditional carriers rounded 30% in 2017 just in Europe, whereas for 2019 increased to 42% and even 62% for Southeast Asia. Other regions, like Russia and Central Asia, have not developed this business model like in the rest of the world, with only 5% of LCCs operations. The global average in 2018 for short-haul operations (<3000 nm) was 33%. The big presence of LCCs in short-haul flights is mainly due to the regional liberalization of the market between neighbouring countries. While this tendency spreads worldwide, the share of the LCCs in the Middle of the Market is also expected to reach around 30-35% in the following years.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.6.

Recommendation 17: MoM aircraft should look carefully to the needs and requirements of the Middle East Region for medium-haul routes.

- **Rationale:** The passenger distribution by distance shows the differences between regions regarding flight distance tendencies. Regions like China, South America and the former Soviet Union (CIS), predominantly travelled shorter distances in 2017, whereas in other regions, like the Middle East, the majority of the air traffic was concentrated in medium- (46%) and long-haul (22%) flights. In Europe and North America, the distribution is closer to the world's average, which was 62% for short-haul, 21% for medium-haul, and 15% for long-haul traffic. 2037 forecast predicts this distribution to change regionally, for example by an increment of the short-haul traffic in China, or an increment of the medium- and long-haul flights in the Middle East. Nevertheless, there is no change forecast in the overall worldwide distance distribution.

Most of the mid-haul traffic is concentrated in the following flows: Middle East – Europe, EEUU – Europe and the Middle East – Northeast Asia, mainly due to business reasons. Figure 13.67 shows that the traffic in the medium-haul segment will be incremented by a factor of 2.4 worldwide, with more importance in some regions like the Middle East, ok, where it will triplicate its demand or the area of Asia-Pacific region. In general, mid-haul traffic will grow at a slower rate than the general traffic, since the regions holding the majority of the worldwide passenger revenue are those where the traffic is concentrated mostly on short-haul flights.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.7.

Recommendation 18: MoM global market will account more than 8400 deliveries between 2018 and 2040, which will justify the R&D and development investment required by a new clean design aircraft specifically design for this market.

- **Rationale:** Forecast values show that global MoM fleet will be 2.5 times bigger in 2040 than what it was in 2018. Some regions will experience a bigger growth in terms of the fleet within this market, which can be translated into Middle of the Market main business focuses. Asian airlines (which include those from Middle-East and Asia-Pacific regions) will account around the 50% of the total mid-haul fleet, whereas Europe and North America will decrease their share of the total fleet from 50% in 2018 to 37% in 2040, as a result of the accelerated growth from the emerging countries. More than 2500 aircraft belonging to the MoM sector will be retired worldwide, and the global market will account more than 8400 deliveries in the forecast period.

The Asia-Pacific region together with the Middle East will account more than 60% of the deliveries within this market, whereas Europe and North America will receive a third of the total new-built aircraft. A total of 588 aircraft will be retired in Europe within the MoM and 520 in North America, which means 59% of the 2018 fleet, will have to be replaced in both cases. Asia-Pacific and Middle-East have different tendencies, with most of the deliveries accounting to the fleet growth, but they will also experience a big renovation of the fleet. Nearly 80% of the 2018 MoM fleet will be replaced by 2040 in Asia-Pacific, and about 90% in the Middle East. 73% and 76% of the deliveries will expand the fleet of the Asia-Pacific and Middle Eastern airlines, respectively. In Europe and North America, these fractions are of 60% and 57% respectively.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.7.

Recommendation 19: The availability of new engines for the MMA will require a new impulse to technologies today at medium TRLs.

- **Rationale:** The new MMA will need a new, next-generation, ultra-efficient engine with a thrust of 18.2–22.7 ton-force (approximately 45,000 lb). Boeing is demanding an engine that burns 25% less fuel for every pound of thrust it produces compared to the 757's decades-old turbines.

The 797 selling case is primarily sustained on the basis of reductions in operating cost. Although Boeing could implement new technologies to reduce its operating costs, it will rely heavily on the engine fuel burn efficiency. This appears to be a key driver in terms of timing – both for program launching and entry-into-service (EIS).

To meet the challenging 2025 EIS engine/s would have to be certified during 2024. That implies an imminent engine selection that would require Boeing's confidence in engine technology that is today in an advanced stage. Since the commissioning date of a new aircraft is scheduled for 2025, the possibilities for engine manufacturers to create and develop fundamentally new engine architectures are limited. In this aspect, the use of current gas generators (cores) of the engine with their subsequent improvement, as a thermodynamic machine, is most appropriate. However, achieving the necessary reduction in fuel consumption in this way can be difficult and costly. It is possible to achieve a significant increase in fuel efficiency by a combined method, namely by an increase of bypass ratio, the use of a geared fan and an increase in engine operating cycle parameters.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.10.

Recommendation 20: Main directions of engine manufacturers' research in terms of engines application until 2025 have been identified in support to the development of new engines for the MMA.

- **Rationale:** The study has pointed out possible directions for the development of power plants in terms of their application in the Boeing NMA. This is due to the relative unavailability of complete information concerning the work of engine manufacturers. That makes sense since it is commercially confidential and its distribution can do much harm to the companies. Development directions are shown in the following table:

Increasing fuel efficiency of engines for long-haul civil aviation aircraft	High-performance thermodynamic schemes of advanced engines for long-haul aircraft
	Model heat exchangers, coolers and regenerators, samples of advanced cooling systems for the engine hot section
	The concept of ultra-high bypass ratio turbofan
Decreasing in specific weight, volume and overall dimensions of engines	Engine configuration with increased specific thrust and extensive use of composite materials
Improving the integration of the power plant and airframe	The layout of the engine nacelle, pylon and wing with minimal noise
	The layout of the power plant and the airframe with common structural elements
Effective modelling of gas-dynamic processes in engine elements Optimization of gas-dynamic characteristics of the elements of engine and power plants Optimal blading of impeller machines	Low-noise, high-performance fan and LPC with a swept and inclined stator and rotor blades
	Fan with ultra-low tip speed at the periphery and a geared drive
	Efficient high-load turbine
	Numerical methods for studying transient and stall processes in ducts, compressors and turbines.
Transient processes in the elements of the engine airflow duct. Transient processes in impeller machines. Ways and means of reducing losses and increasing stall margins	Methods for diagnosing transient processes in impeller machines
	Active methods for controlling flow ducts, compressors and turbines (MEMS technologies, barrier and corona effects, microwave plasma).
	Active methods for increasing the stall margins.
	Superggressive transition ducts of GTE with a flow control system
	The design of spray units to operate with fuels of different fraction composition

Creation of methods and means for increasing the efficiency of mixing and combustion processes.	Method of organizing work process in the main combustor at low excess air factors and high gas temperatures (near-stoichiometric combustion with T>2000 K)
Creation of methods and algorithms for modelling the processes of the air-fuel mixture.	New highly efficient fuel burning schemes. New designs of gas turbine power plants combustors
Creation of physicochemical and mathematical models and methods for calculating the main characteristics of the processes in various combustors	New algorithms and methods for numerical modeling of high-temperature reactive flows using high-performance computing technologies

- **Justification:** What if analysis 1: “The MMA case”, chapter 13.2.10.

Recommendation 21: Engine manufacturers will need to capitalise its technological innovation capability and to surmount reliability problems in their more recent models.

- **Rationale** Three companies - CFM International, a joint venture between General Electric and Safran, Pratt & Whitney and Rolls-Royce, are specified as applicants for the project to develop a new engine.

The reviewed companies have the technology and potential to develop a new engine for a Boeing NMA within a specified timeframe, which makes the choice of a future engine supplier unclear. At the same time, companies must be confident in the success of future aircraft. This confidence will be determined by the correctness of the Boeing strategy selection and the forecast of the future passenger transportation market.

However, engines manufacturers are suffering some reliability problems that bring doubts about whether engine makers will have the capacity to support a new programme with service entry in the 2025 timeframe. Rolls-Royce is dealing with turbine and fan blade problems on some Trent 1000s that are one of two engines that power 787s. Pratt & Whitney’s geared turbofan engines have suffered durability and other issues that have spoiled the service entry of the A320neo. The joint venture Safran-General Electric has had several problems with its LEAP engines relate to the appearance of cracks in the low-pressure turbine section, which forced Boeing to halt test flights of its 737 MAX jets. Those problems have affected a portion of the fleets and manufacturers are dedicating substantial resources to solve these issues.

- **Justification:** What if analysis 1: “The MMA case”, chapter 13.2.10.

Recommendation 22: Short term improvement in power plants shall consider the aerodynamics of the air-gas channel of the engine and its nacelle, the use of ceramic composite materials for combustion chambers and turbines, the use of new alloys for compressors and other engine elements.

- **Rationale** All three considered companies use similar directions to improve power plants based on improving the aerodynamics of the air-gas channel of the engine and its nacelle, the use of ceramic composite materials for combustion chambers and turbines, the use of new alloys for compressors and other engine elements. This is determined by the desire to improve the weight perfection of the engine, to increase the parameters of the operating cycle, to reduce losses in the engine, etc. A significant difference is the use of a geared fan in the PW 1000G engine family. The company gets the operating experience of such systems and the ability to foresee and eliminate possible problems when creating a larger engine for the Boeing NMA aircraft. This aspect may be one of the key factors that will affect the choice of engine supplier for future aircraft.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.10.

Recommendation 23: Consider the implications and potential of additive manufacturing in engine production.

- **Rationale** The additive manufacture technology (3d printing) will most likely become a significant production factor that may affect the commissioning date of a new engine. The potential of this factor is not yet fully appreciated. The desire of companies to increase the number and range of manufactured parts using 3D printing indicates the possibility of a significant increase in production rate. How this will affect the commissioning date of a new engine is not reliably known.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.10.

Recommendation 24: Full exploitation of the MoM requires the accomplishment of a set of objectives: i) open new and profitable markets, ii) enable new business models, iii) increase profits on existing routes, iv) restructure networks for better-operating efficiency and v) reduce turn time-increase aircraft utilization.

- **Rationale:** Latest and more efficient aircraft (A320, B737, B787,...) with a higher number of seats and longer-range capabilities have helped companies to open new routes, previously not economically viable with other aircraft. Over the last few years, aircraft with new capabilities opened some 400 new routes that existing aircraft could not do because they did not have the economics. This will create a new fragmentation of the market. A good example of new routes opened thanks to new aircraft introduction is the new generation of long-range aircraft such as the Boeing 787 and the Airbus A350, which were able to open the longest routes ever seen in the market.

LLC is expected to flourish in the MoM, where today represent just a small percentage of the operation. Air transport liberalisation in emergent economies will set the basis for an optimum scenario that an MMA can make a reality.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.6 and 13.2.11.

Recommendation 25: The development of a new aircraft in a relatively small market, with high levels of competency from several different models, requires the manufacturer to get its supply chain aligned with a price that customers are willing to pay.

- **Rationale**. Boeing estimates a market for the jet of between 2,000 and 4,000 airplanes. Some analysts have predicted that the development of the new Boeing 797 jet will cost between $15 billion and $20 billion, while other analysts think that an ideal budget would be 13,5$ billion. Besides, it is estimated that Boeing will need to sell between 1,045 and 1,585 aircraft units so that the new model is profitable. Higher development costs or jet sales lower than expected could reduce or eliminate profits on the 797. Net Present Value obtained by a company from the exploitations of its product lines is very much sensible to selling prices. This impact will be even more important considering the relevance of discounts in this market.

Boeing must get its supply chain aligned with a price that customers are willing to pay. Analysts suggest that a competitive price would be roughly $76 million per airplane, making a list price somewhere between $130 and $150 million. That would be cheaper than the 787 Dreamliner (listed at $239 to $281 million) and the competing Airbus A330 ($238,5 million).

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.11.

Recommendation 26: To favour the innovation that comes with a new clean-sheet aircraft, manufacturers should not only invest in R&D but should also make biggest efforts on the standardization of the production process to improve its learning curve as soon as possible.

- **Rationale**. Recurring costs of production are subject to a learning curve. This process is characterized in aircraft production by a significant decrease in unit cost as additional aircraft are built, eventually reaching a unit cost approximately constant. That is, the more aircraft produced, the more the manufacturer learns and the cheaper the next aircraft can be produced. The learning curve depends on a parameter known as "slope", which describes the magnitude of the learning curve effect. A slope of 100% indicates no learning (the initial unit cost remains constant throughout the production run). Aircraft production typically follows a 75-85% learning curve.

The learning curve can be one of the parameters influencing the more in the projected profits manufacture can obtain from its models, particularly when the number of expected units is not as high as in the single-aisle market. At the beginning of the learning curve, costs are higher so manufacturers in the MoM will have an incentive to improve their learning curve as soon as possible.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.11.

Recommendation 27: The unbalance situation in the MoM, with non-symmetric reengineering possibilities and costs for both manufacturers, will favour new aircraft design and innovation.

- **Rationale:** Since the early '80s, every move of one competitor was mirrored by the other. Nearly each of the airplane types in the portfolio of Boeing had, has and probably will have a counterpart in Airbus. This might not be longer the case in the middle of the market, as an unbalance situation is taking place in the MoM. The possibilities of both manufacturers for re-engineering incumbents' models are not symmetric.

The increasing sales of the A321neo are allowing Airbus to capture the mid-range market, surpassing the sales of the largest variants of the Boeing 737 MAX. A321neo is a fundamentally stronger aircraft than B737, both in terms of operating and unit costs (excluding pricing), and in terms of operating performance on metrics like payload and range. Therefore, Boeing needs and offering in the MoM space, or it will miss out on thousands of new jet sales over the next 20 years in this market segment.

With Boeing's market share declining and Airbus share increasing, and B737 MAX evolution possibilities almost exhausted, Boeing has no other alternative than proposing a new clean-sheet design aircraft.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.14.

Recommendation 28: The dominance of the MoM being at stake will favour the consolidation in the next 5 years of aerospace technologies today at medium TRL stages under a broad set of scenarios and will shorten the final step of its development.

- **Rationale:** Due to payback periods on the order of 10-15 years for large commercial aircraft programs, when manufacturers commit to a course of action, re-engineer or new aircraft, they lock-in to the technology level for the duration of the program to recover part of the investment, enabling only incremental improvements. They have also to assume the risk that comes with big investments.

If Boeing confirms its decision for the B797 in 2020, it will be locked with the technology that in 2020 is at high TRL stages. This might imply a short-term impulse for these technologies that will be shortened their final development with regard to a normal development cycle.

- **Justification:** What if analysis 1: "The MMA case", chapter 17 and 18.

Recommendation 29: The perspective of low fuel prices might induce both manufactures to retain efforts in research in favour of increasing profits for the manufacturer's best in class products. This perspective could only be contested institutionally by fomenting R&D or by regulation forcing new technologies.

- **Rationale:** Under a scenario of expectation of low fuel prices, fuel efficiency is not expected to be the main driver of the market share, and the forces governing the market share today will remain more or less stable. Other factors will dominate the buying decision by companies, such as maintenance costs, other operational costs, manufacturer fidelity, the economy of scale, number of seats, etc.…

In this scenario, neither Boeing nor airbus will have an incentive to invest in fuel efficiency technologies, either in the airframe or in the engine. None of them can increase the selling price of a new aircraft due to the fact that the savings in fuel cost are not significant considering the lifespan of the aircraft.

The results of the game analysis show that the situation of equilibrium in this scenario is achieved if Boeing maintains its product lines and Airbus evolves to the A321XLR, despite the losses in Boeing market share.

- **Justification:** What if analysis 1: "The MMA case", chapter 13.2.14.

13.2.1 Introduction to the What if Study

The PARE project assess progress, gaps and barriers, and propose suitable measures to close the remaining gap to support the achievement of the Flightpath 2050 goals in a broad variety of key areas of aeronautical research which are essential for the development of the aerospace sector in Europe.

As part of this process, the project has the task of identifying the actions required in the coming future for the proper development of the aerospace research sector, which can benefit from a detailed and rigorous analysis of possible political, social and industrial scenarios by carrying out What if analysis.

The experience of the consortium and its capabilities, as well as the work performed in analysing the state of the art, and future forecasts and needs in each of the project's areas of interest, have allowed the identification of two highly relevant case studies for the evolution of the sector.

The first case is justified from the perspective of the growth forecasts of the air transport sector in the medium and long term that identify the Asian emerging economies, and in particular China, as the one with the highest growth in air transport. Coupled with the booming economic development of these regions, we are witnessing the growth of the potential powerful aerospace industry in China. The capacity of this thriving industry to consolidate will undoubtedly condition the worldwide scenario of aviation.

In recent years, we have observed several attempts by the Chinese industry to develop and certify large transport aircraft, such as the regional jet ARJ21 certified by the CAAC after years of delays, the C919 in the single-aisle segment whose certification has been postponed for years, or the future development of a wide-body model C929. How the success of all these attempts will effectively affect the Airbus/Boeing leadership in the industry is going to be one of the big issues in the industry in the coming years.

China's ability to certify and produce commercial aircraft efficiently, economically and on time to take advantage of the country's anticipated development could greatly influence the international scenario and could have a major impact on the current balance of the aerospace industry.

Keys in that future will be the capacity of the Chinese industry to certify its current aircraft developments, produce on a large scale, gain the confidence of the airlines and acquire a significant share of the market. All these aspects are raised and developed in a first case study that aims to shed light on how the possible scenarios can influence the development of the European air transport industry and how Europe can react in each case with the best at political, regulatory, research, educational and industrial strategy.

The second case focuses on the analysis of competition among the main aircraft manufacturers in a segment that has captured the attention of both in recent years, the Middle of the Market segment.

The middle of the market is often abbreviated MoM or referred to as MMA for Middle of the Market Aircraft. It represents the airliner market between the narrow-body and the wide-body aircraft as well as between the short and the long range and has become a market segmentation used by Boeing Commercial Airplanes since at least 2003.

These aircraft can fly ranges of approximately 3,000 to 6,500 nm and carry passenger loads of approximately 180 to 300 people in both single and twin-aisle configurations. Both Airbus and Boeing produce aircraft that serve this segment. In the range of 2,500 to 4,000 nm, 120-169 seat narrow-body airplanes are also mainly used, and 170-229 seat narrow-body jets (A321, 737-900ER, 757, etc.) and 230-399 wide-body jets (A330, 767/787, etc.) are operated. In the upper band of this range, partly because the route distance is longer, relatively large airplanes such as 170-229 seat narrow-body and 230-399 wide-body jets are used more actively than for over 3,500-4,500 nm. In the range of 4,500 nm or more, 310-399 seat jets (A340, 777, etc.) are mainly operated, followed by 230-309 seat jets (A330, A350, 787, etc.), 500-800 seat jets (A380), and 400-499 seat jets (747). 400-499 seat airplanes have declined in number due to the recent decrease in the number of 747 and A380 jets orders.

B737 and A320 are the best sellers' products, with more than 10,000 and 8,500 deliveries respectively. B737 is in its third generation since 1969s and A320 in its second generation since the 80s, however, this third 737 has less stretch potential than the A320, and the 737 MAX 9 has been beaten soundly by its rival Airbus' A321neo in the 170-229 seats market segment by a ratio of nearly 8:1 looking purely at current firm orders. There is a 100 seat gap between the 737 and 787 where Boeing needs and offering to compete with the A321 and profit from the 757 and 767 replacement opportunities. The issue has become more burning since Boeing began studies for the development of an MMA, named today as 797. Up to now, the company has been delayed the decision about whether to move forward with the 797 program and lately has announced that probably a decision will be made in 2019. On the other hand, forecasts of traffic growth are especially optimistic for this sector and have led the industry to focus strategies in recent years on the real volume of the MMA market and how large manufacturers value its potential and develop strategies to lead it.

Because of all these reasons, the second case addresses the analysis of the MMA case and the best and most probable Airbus and Boeing strategies to succeed in this market.

Objectives

The main objective of this "what if" study is to analyse and study the possible evolution of the Middle of the Market Aircraft sector and the prospects of the Boeing MMA to provide insight into what opportunities may arise from its development and to inform future policy, research and business strategies through a set of synthetic conclusions and recommendations.

To achieve this aim, the study pretends to gather analytics and insights to answer key technical, market and business questions about this mid-size aircraft and its impact on the market. Key issues that will be covered by the study include:

- A thoughtful understanding and quantification of the MMA market, considering its main drivers and possible evolution, the reasons why airlines are interested in this size of aircraft, and which regions and companies offer the best sales prospects.
- An insight into how the large aviation market is divided nowadays between two main manufacturers (Airbus and Boeing), and a better understanding of the causes and the consequences of this duopoly.
- A solid, supported by data and analytics, answer to the questions: Will Boeing launch an MMA aircraft? And when? What is a realistic price for such an aircraft? How many aircraft might Boeing sell?
- A data-supported guess of what the Airbus reaction and strategy to maintain or even improve market positions might be pre-emptive and reactive.
- Provide details in how realistic is to use modernized engines in extra-large aircraft such as the A380 and answer the following questions: Is it the extra-large segment over and conquered by twin-engine smaller options of jetliners? Or there is still a real need for airlines to use these models?

The study will make the best out from data and expert information covering market structure, forecast, airlines needs and requirements, production and sale prospects, cost and price figures, aircraft value criteria, SWOT and game theory approach to better understand what is happening and what could happen in this sector.

Scope

Besides the overall questions about the prospects of the Boeing MMA, the "what if" analysis will address the following issues:

- **The lessons learned from the past A320 vs B737 competition.** The Boeing B737 is in its third generation since the 1960s and the Airbus in its second since the 1980s. With more than 10000 deliveries of the B737 and 8500 of the A320, they are the numeric best sellers in the Boeing and Airbus ranges. With current backlogs numbers, they might exceed 12000 or even reach 15000 sales. Though wide bodies are worth more individually they are most unlikely to approach those numbers, so in overall market values, these 'smallest' airliners are quite big and worth competing for. What does their long history tell us that was relevant in the past and might be also in the future?
- **The A321LR/A330 as replacements for the B757/B767.** The third generation B737 has less stretch potential than the second generation A320. The new generation of more efficient engines has turned the A321 into more than its designers could originally have hoped for: an aircraft for long thin routes able to cross continents and some oceans. The B737 cannot be similarly stretched so Boeing as no current challenger for the A321 in the B757/B767 market for long thin routes. Airbus says that the stretch potential of the A321LR is not yet exhausted and the A330Neo is a bigger option. Will this satisfy the market? Is there a gap for something more modern and efficient?
- **The timeframe for the Boeing MMA.** In order to upstage the A321LR/A330 neo, the Boeing MMA must be a twin-aisle with 220-270 seats and more modern engines than the B737max/A320neo and cannot be available before 2023. Since the current most advanced engines in the class, thePratt&WitneyPW1200 geared fans and the Snecma-General Electric leap are having development and /or reliability problems, can much better performance be expected soon after for the new MMA engines? Is there a market for just one or more new engines?
- **Are the A321LR/A3330neo a short or long-term response?** The A321LR (and A330 Neo) are available here and now, absorbing the B757/B676 replacement market for several years until the Boeing MMA offers an alternative. Will this dry up the market and void the bossiness case for the Boeing MMA? Could Boeing come up with a short-term competitor as an updated B767 or would this be unpromising as an investment? Will airlines wait for the Boeing MMA? Is there both a B757/B767 replacement and a new long thin route market that will justify the Boeing MMA in any case?
- **Will an all-new Airbus MMA be needed?** If the Boeing MMA goes ahead as a more modern aircraft how much more efficient will it be than the A321LR and A330 neo? How long will these remain attractive in the market? Can their lifetime in sales be prolonged? Will Airbus have to counter the Boeing MMA with an all-new design? Since Airbus will have the hindsight on the Boeing MMA how much better could it make the Airbus MMA? What would be the timeframe for an Airbus MMA to give the Boeing MMA no room between the A321LR and a new Airbus rival? Is Boeing in a corner with no easy exit?
- **New MMA engines to revive the A380**. Could the development of the Boeing MMA not only face difficulties in competing profitably with Airbus in the long thin market but also have other consequences? Currently, the A380 is surviving on marginal production numbers, and its layout of 4 old engines can hardly compete with modern long-range twins. There are no modern replacements for the A380 engines, but the MMA could fall just in the right thrust

bracket. Could the MMA engines revive the A380 to compete with modern long-range twins? Since the Boeing MMA is almost certain to be all-electric with bleed fewer engines would the development of engines with bleed for the A380 be economical (turning the A380 all-electric) might be even costlier? Could the market prospects of an A380 with MMA engines justify the development?

Methodology

The methodology proposed in this case study is double. On the one hand, the "what if" analysis follows a qualitative and analytical approach typical of market and competition studies. This approach alone is sufficient and adequate to respond to the questions and cases raised in the objective and scope of this study. Additionally, the "what if" analysis is complemented with the application of game theory to evaluate the results of the possible competition strategies of Boeing and Airbus in this specific market sector considering a medium and long-term horizon. Additionally, the game theory will allow performing sensitivity analysis to consider the impact of the various uncertainties that influence the case.

Information and analysis coming from the first part of the analysis will be used to define the structure of the competitive games in the second part of the analysis and the possible scenarios; as well as to synthesize the possible strategies of the two players and to construct the aircraft valuation model for the estimation of the payoffs. Figure 13.1 illustrates the main steps in the whole process.

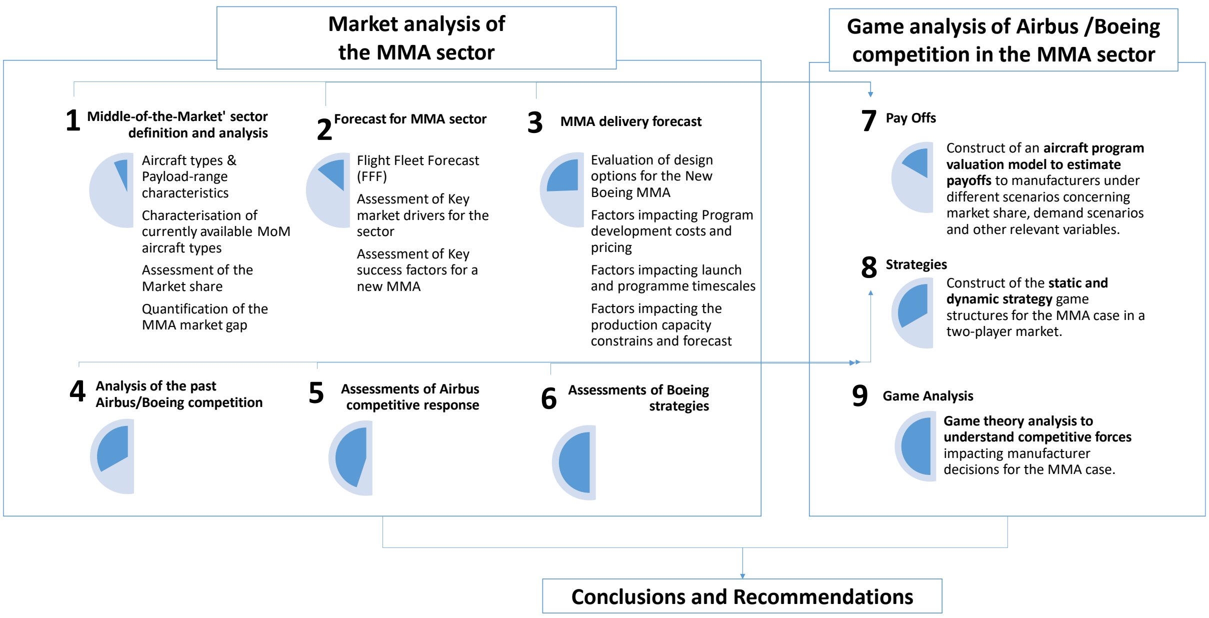


Figure 13.1. Methodology for the "what if" study on the MMA case.

As can be seen in Figure 13.1, the initial market analysis consists of 6 main steps. The first step involves the definition and analysis of the Middle of the Market's sector itself. In this step, the sector is analysed in terms of aircraft types and payload-range characteristics. The different approaches of Boeing and Airbus to the definition of market sectors are explored. The models that both companies have currently available or are already committed to developing are analysed in detail in term of performances and adequacy to the MMA sector and finally, the actual market share picture is analysed. As a major outcome of this first step, the questions of the existence of an MMA market gap, and its magnitude, if any, will be answered.

The second step is concerned with the following main topics: i) Flight Fleet Forecast (FFF); ii) identification of key market drivers for the sector; iii) identification of key success factors for a new MMA; iv) performance of a SWOT analysis for the Middle of the Market Aircraft. Traffic and fleet forecast will be a critical element for the valuation of the viability of the Boeing MMA, and at the same time, it will be one of the main sources of uncertainty in this case study, particularly considering the long-time frame of the study. To cope with such limitations, the study will consider most accurate and reliable forecast and will complement them with our own PARE project estimations based on accepted forecasting methodologies and hypothesis based on the best knowledge within the consortium. Those inputs will serve to generate a set of credible forecast scenarios, including a baseline forecast and ranges, to be considered during the sensitivity analysis.

The third step focuses on the MMA delivery forecast trough the evaluation of i) the design options for the New Boeing MoM; ii) the factors impacting program development costs and pricing; iii) the factors impacting launch and programme timescales vi) the factors impacting the production capacity constraints and forecast.

Finally, steps 4, 5 and 6 are dedicated to outline and evaluate the possible Airbus reaction strategy, as well as the alternatives strategies that Boeing might apply for the MMA sector. Step 4 will look at what the long history of competition between Airbus and Boeing tells us it was relevant in the past and might be in the future, particularly in the single-aisle segment but also in other segments. Step 5 and 6 outline the respective possible Airbus and Boeing strategies to compete in this market.

Additionally, as can be seen in the figure, the game competitive research approach is three staged (steps 7, 8 and 9). In step 7, static and dynamic game structures for a two-player MMA market are constructed. In step 8, using the outcomes of previous study sections, an aircraft program valuation model is implemented to estimate payoffs of manufacturers under different market share and demand scenarios. The purpose of this model is not to determine aircraft manufacturers' profitability precisely, but to estimate the rank of payoffs to determine how changes in the market structure may change the equilibrium game outcome. It has to be noticed that this analysis will be hindered by the proprietary nature of aircraft program economic data. The consortium uses reusable assumptions based on publicly available data sources. These assumptions will also be subject of a sensitivity analysis to determine the impact of the assumptions and proxies on the study's funding. Finally, at step 9, a game theory analysis is used to model competitive forces affecting manufacturer decisions.

The results of the whole process will allow us to understand how the competition will affect the decision to invest in new aircraft designs in this market. It will also help us to understand how the introduction of a new Boeing MMA could imply changes in a today almost symmetric duopoly, or how it will incentive the development and introduction of new technologies and aircraft improvements. This understanding and the derived conclusions and recommendations may assist policymakers in developing regulatory and incentive mechanisms to improve aviation and inform expectations of the introduction of new aircraft into the global aviation market. The whole approach will also allow testing policy options to determine their outcomes in a competitive market, based on the assumptions in the valuation model.

13.2.2 Middle-of-the-Market' sector definition

There is a certain confusion or lack of clear definition about what the middle of the market (MoM) is, up to what extent it is a real opportunity and how the various existing and potential Boeing and Airbus designs stack up against one another.

Attending to how airplanes are used depending on the route length, a few years ago, commercial aircraft were clustered in two quite differentiated segments. For short-haul routes, the Boeing 737-800 and Airbus A320 were the main options, with capacities around 150-160 seats in a two-class configuration and flying distances of about 2,500-3,000 nm. For their longer international routes, airlines mainly used large planes such as Airbus' A330-300, Boeing's 787-9, and Boeing's 777-300ER, which 250-350, or more, seats in a typical premium configuration, (with full flat-bed business class seats), and a fly distance of 6,000 nm or more.

However, the airlines' preferences are changing towards planes that span the size and range gap between the traditional narrow-body and wide-body segments. This size/range gap is the MoM – Middle of the Market- segment, which remains poorly defined except for the characteristic of being in the middle. With a broad interpretation, the MoM segment covers aircraft carrying 150 to 250 passengers in a typical high-quality typical premium-heavy international configuration (long-distance configuration, including flat-bed business class seats). In addition, although all aircraft in this size range can fly at least 3,000 nm, some airlines want to fly distances of 4,000 nm or up to 5000 nm with an airplane of this size. Some authors broadly define the MoM sector as above the Boeing 737/Airbus A321 and below the Boeing 787/Airbus A330-200/800. Since 2003, Boeing has extensively discussed the MoM denomination and concept[1], as a market between the narrow-body and the wide-body aircraft, although the manufacturer has not yet formally incorporated it into its market forecast.

Both Airbus and Boeing produce aircraft that serve this segment. In the Boeing line-up, it is between:

i) the largest Boeing 737 MAX 9 of 194,700 lb (88.3 t) of maximum take-off weight (MTOW) for 178 passengers in two classes over a 3,515 nm (6,510 km) range;
ii) and the smallest Boeing 787-8 of 502,500 lb (227.9 t) for 242 passengers in a 2-class configuration over a 7,355 nm (13,621 km) range.

This segment was previously covered by Boeing with:

i) the largest modern narrow-body, the Boeing 757, typically the -200ER for 200 passengers over 3,915 nm (7,251 km) with a 255,000 lb (116 t) MTOW; and
ii) the smallest wide-body, the seven-abreast Boeing 767, typically the -300ER for 269 passengers over 5,725 nm (10,603 km) with a 412,000 lb (187 t) MTOW.

In the Airbus line-up, it is between:

i) the A321LR of 97 t (214,000 lb) of MTOW for 206 passengers in two classes over a 4,000 nm (7,400 km) range[2], and
ii) the A330-800neo of 242 t (534,000 lb) for 257 passengers in three classes over a 7,500 nm (13,900 km) range.

Taking into account Boeing and Airbus' products line and according to several sources, the Middle of the market segment can be located in the middle of the traditional narrow-body and wide-body segments, covering aircraft which can carry around 175 to 300 passengers in a two-class configuration and have a range between 3000 to 6000nm[3]. However, the previous definition is broad and its boundaries are very blurred so that the MoM is not currently clearly defined. For this reason, the aim of this study is to define clearly this segment as well as the aircraft, which are currently operating in it, which is provided in the next sections.

13.2.2.1 Boeing vs Airbus definition of market segments

There are some differences in how Boeing and Airbus categorize planes, which might lead to inconsistencies in the data about market share and forecasts (see Table 13.11).

Traditionally, Boeing has classified planes as single-aisle or two-aisle and then subcategorizes by the number of seats. Therefore, within the narrow-body segment, there are regional jets, planes with 90-175 seats, and planes with over 175 seats. Within two-aisle planes, there are small, medium, and large which categorize planes by the number of seats.

Traditionally, Airbus has broken the fleet up into single-aisle and twin-aisle planes, but they reserved a category for very large aircraft. However, in 2018 Airbus has introduced a new market segmentation in its 2018 forecast. It has changed the segmentation methodology dividing segments into categories ranging from 'Small' to 'Extra Large' (see Table 13.1), blurring the traditional boundaries between aircraft types. This new classification redefines the traditional distinction between single-aisle or narrow-body jets and double-aisle or wide-body jets, and between the various types of long-haul aircraft. The "small" aircraft market goes up to 230 seats and ranges up to 3.000 nm. "Medium" category is between 230 and 300 seats and range up to 5.000 nm; and "Large" between 300 and 350 seats and range up to 10.000 nm. In the larger aircraft, instead of segmenting aircraft with 450 or more seats, which in practice means creating a specific category for the 747 and the A380, Airbus now places all aircraft with a capacity above 350 seats and range up to 10.000 nm in a category called 'Extra Large.'

Boeing classification	Aircraft	Airbus classification
Regional	Antonov An-148, -158	Small
	AVIC ARJ-700	Small
	Bombardier CRJ	Small
	Embraer 170, 175, 175E2	Small
	Mitsubishi MRJ	Small
	Sukhoi Superjet 100	Small
Single-Aisle	Boeing 737-700, -800, MAX-7, MAX-8	Medium
	Boeing 737-900ER, MAX 9, MAX 10	Medium
	Boeing 757 -200, -300	Medium
	Airbus **A318**, A319, A320, A319neo, A320neo	Small
	Airbus A321, A321neo	Medium
	Bombardier CRJ-1000	Small
	Embraer 190, 190E2, 195, 195E2	Small
	Comac C919	Small
	UAC MS 21-200/300	Small
	Tupolev TU-154, -204, -214	Small/Medium
Wide-Body	Boeing 747	Extra-Large
	Boeing 767	Large
	Boeing 777, 777X	Large/Extra-Large
	Boeing 787	Large
	Airbus A330	Large
	Airbus A340	Large
	Airbus A350	Large/Extra-Large
	Airbus A380	Extra-Large
	Illyushin IL	Large

Table 13.1. Passenger's aircraft segments according to Boeing and Airbus. Aircraft in bold are no longer in production. Sources: Boeing, Airbus.

Figure 13.2 shows, through a Payload-Range diagram, the differences between the two manufacturers' segmentation of the market.

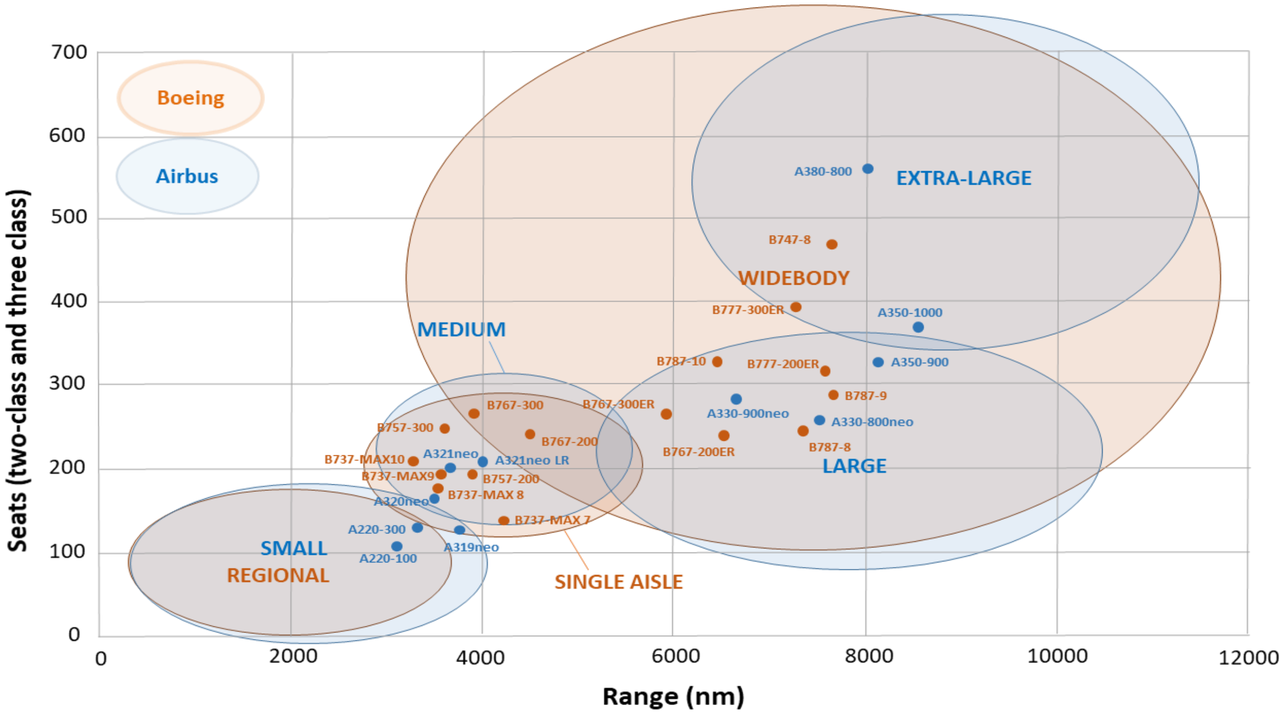


Figure 13.2. Differences between Airbus and Boeing's market segmentation.

The change in Airbus segmentation methodology has a history behind it. Airbus has been waging a statistical battle for years with Boeing over the actual demand for aircraft such as the 747 and the A380. Airbus argues that the demand for these aircraft will grow in the future due to the problems of airports congestion. Boeing thinks that large twin engines like the 777X will absorb most of this demand and that the four-engine jets are seeing their last years. Today, Boeing's vision seems more realistic, but congestion at some point may force decisions.

Comparing how aircraft are operated today and in 2007 (Figure 13.3), it can be seen the evolution and scope by market segment in terms of range and number of seats. The figure shows that size is increasing with a clear overlap between segments, reflecting a blurring of the boundaries between market segments. Today, for example, larger single-aisle types like the A321 operate in what would have been considered a twin-aisle market space. This is not just true for the single-aisle types; larger aircraft like the A350 can operate in a number of segments depending on airline or market requirements.

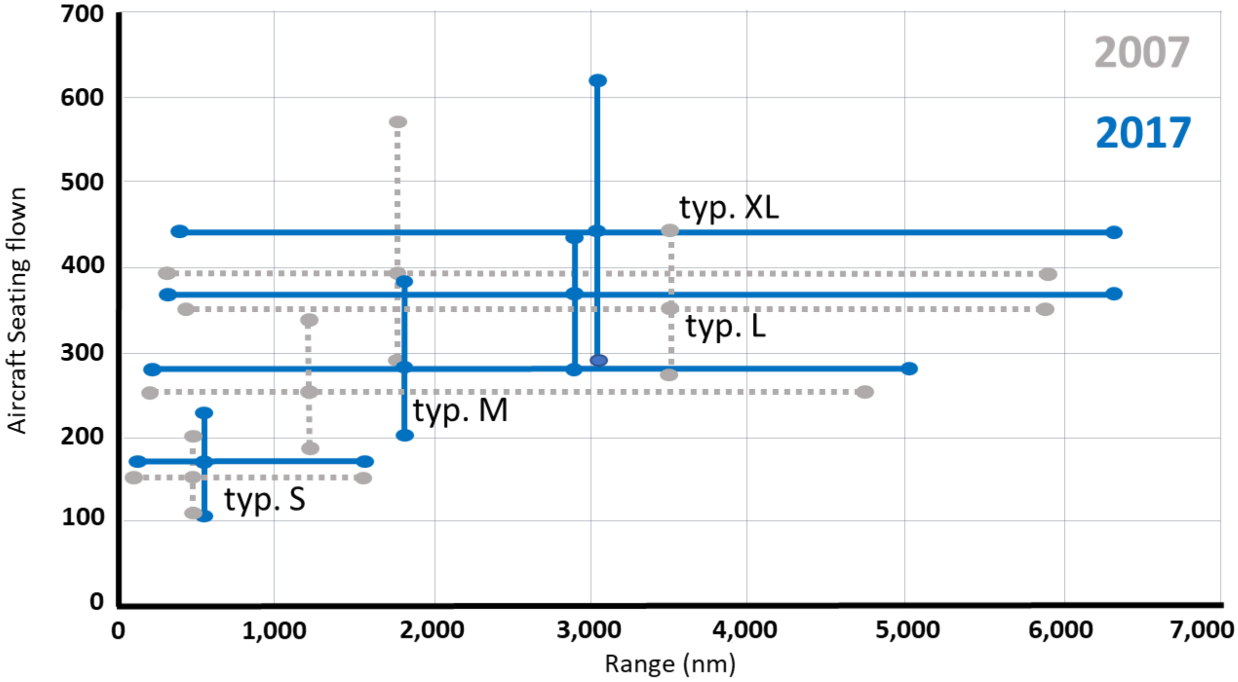


Figure 13.3. Blurring boundaries between the new Airbus aircraft market segmentation. Sources: Airbus CMO 2018.

The change in methodology is based on the way in which airlines use their airplanes instead of the type of model. Airbus' new statistical framework does not take into account the number of engines and focuses on the segments by the number of seats, reflecting the opinion that long-term forecasts do not have to coincide with current product lines.

13.2.2.2 Narrow-body vs wide-body aircraft for the MoM

The main characteristic of the MoM segment is the diffuse frontier between the aircraft operating in it. The routes considered as "MoM" sometimes can be covered by both narrow-body and wide-body, and operators use indistinctively these two types. Nevertheless, there are some differences between them, especially when it comes to customer comfort or operating costs.

Narrow-body aircraft. Smaller, single-aisle airliners are the favourite ones of the airlines since their operating costs are substantially lower than wide-body airliners. The maximum capacity of these aircraft is around 240 seats in 1-class configuration and with 28" pitch. The new engine improvements on the new models such as the A321neo LR with lower fuel consumption have allowed these single-aisle aircraft to cross the Atlantic offering a 27% lower fuel consumption than the previous generation's Boeing 757. One of the advantages of flying small airliners is that it is not necessary to have a very high occupation factor to make a profit out of it. On the other hand, the comfortability is limited due to the limited space. The strategy of airlines nowadays is offering flights with a lower number of available seats but increasing also the frequency. Thus, flying is profitable, allows flexibility of scheduling and satisfies the passengers' demand.

Wide-body aircraft. Big jets are usually more comfortable and the favoured ones of the customers due to the higher pitch and the bigger size of the seats. The design of these aircraft is initially thought for long-haul flights, carrying more passengers for long hours of flight. Additionally, its design allows passengers to move easier due to its double aisle configuration. Operating these aircraft in short-haul flights is not impossible but difficult. For a flight to be profitable, it is necessary to sell a high percentage of the tickets, since the fuel consumption per seat ratio is bigger than in narrow-body aircraft. On the other hand, bigger jets allow flexibility in airport operations since the number of flights is reduced, which can be a medium- or long-term solution to avoid airport congestion.

Figure 13.4 shows the CASM (Cost per Available Seat Mile) of different types of aircraft along with their number of seats, according to the average length of the flight. Although there is not a really defined tendency, it can be seen that long-haul flights flown by larger aircraft such as the Boeing 777 or Airbus A330 have the lowest costs per seat. In addition, from the figure, it is deduced that wide-body aircraft operate at a lower cost whereas the distance is longer.

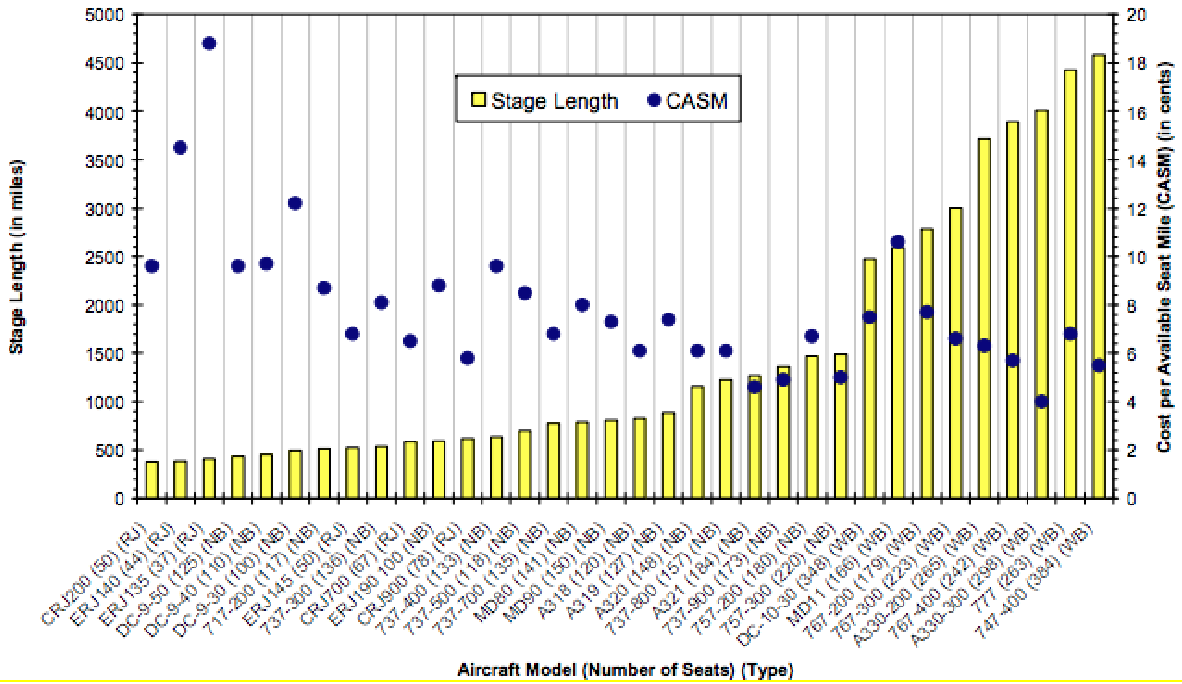


Figure 13.4. Cost per ASM and average stage length by model. Source: The Boeing Company.

13.2.2.3 Payload-range characteristics

One of the most widespread means used to analyse an aircraft performance is by evaluating its payload-range performance, which can be illustrated graphically through the payload-range diagram. This diagram allows examining the capabilities and limitations of an aircraft related to its operating requirements as well as to compare an aircraft operating economics.

First of all, it is important to note that assessing a payload-range diagram includes analysis of the airplane operating weights, which are essential components that affect significantly the aircraft payload-range performance. In particular, payload-range analysis involves examining Maximum Take-off Weights (MTOW) and its various components to assess the aircraft's payload capability at different ranges, as well as range capability with different payloads.

On the other hand, the operating costs of an aircraft also depend solidly on its empty-weight, which is related to the structure that the aircraft carries. The empty weight of an aircraft designed for long-haul flights is heavier due to the higher amount of fuel that it must carry as well as the bigger structure required to fly longer distances.

Therefore, there are several aircraft weights that must be considered for payload-range diagram analysis, which can be categorized depending on how they are certified, existing two types: those weights that are certified by the manufacturer during the design and certification of an aircraft, and those weights certified by the operator. Figure 13.5 below illustrates the composition of weight categories that are reflected in most commercial aircraft as well as the most important definitions that are required to understand the payload-range diagram.

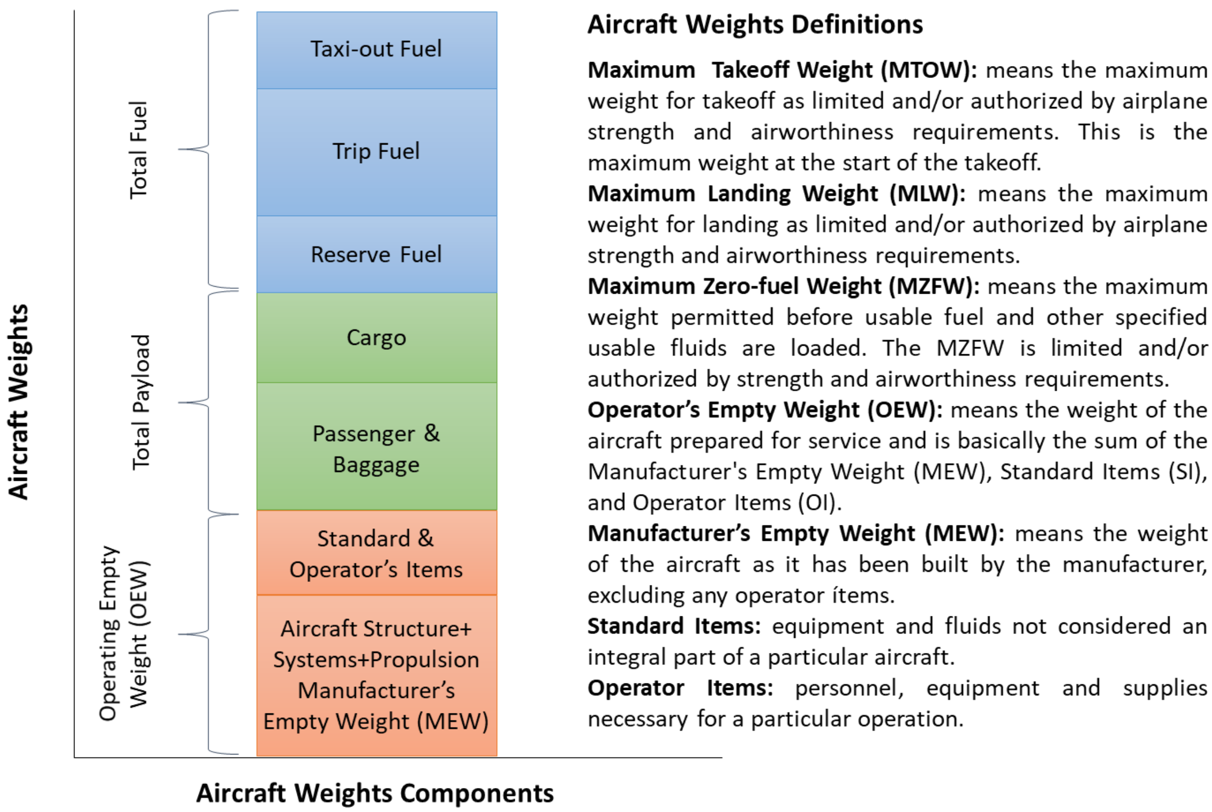


Figure 13.5: Aircraft weights composition

Once the main weights related to the payload-diagram have been described, the next step is examining how the different weights of the aircraft are built-up with reference to its payload-range diagram.

The payload-range diagram is useful for operators in:

i) comparing payload range capabilities of various aircraft types
ii) determining how much payload can be flown over what distances according to a set of operational limitations.

The specific shape of the aircraft's payload-range diagram is affected by its aerodynamic design, structural efficiency, engine technology, fuel capacity, and passenger/cargo capacity. Each aircraft has its own corresponding payload-range diagram, with different limitations depending on the engine type installed.

Figure 13.6 shows a typical payload-range diagram. For all aircraft, there is a natural trade-off between its payload and range performance, since increasing distance by reducing payload may not profitable for the operator. The typical shape of the curve is such that the aircraft is able to carry a maximum payload over a specified range. Longer ranges can be flown if an operator is willing to reduce its payload in exchange for fuel. In the last section of the curve, the trade-off consists of compromising payload in order to achieve greater range.

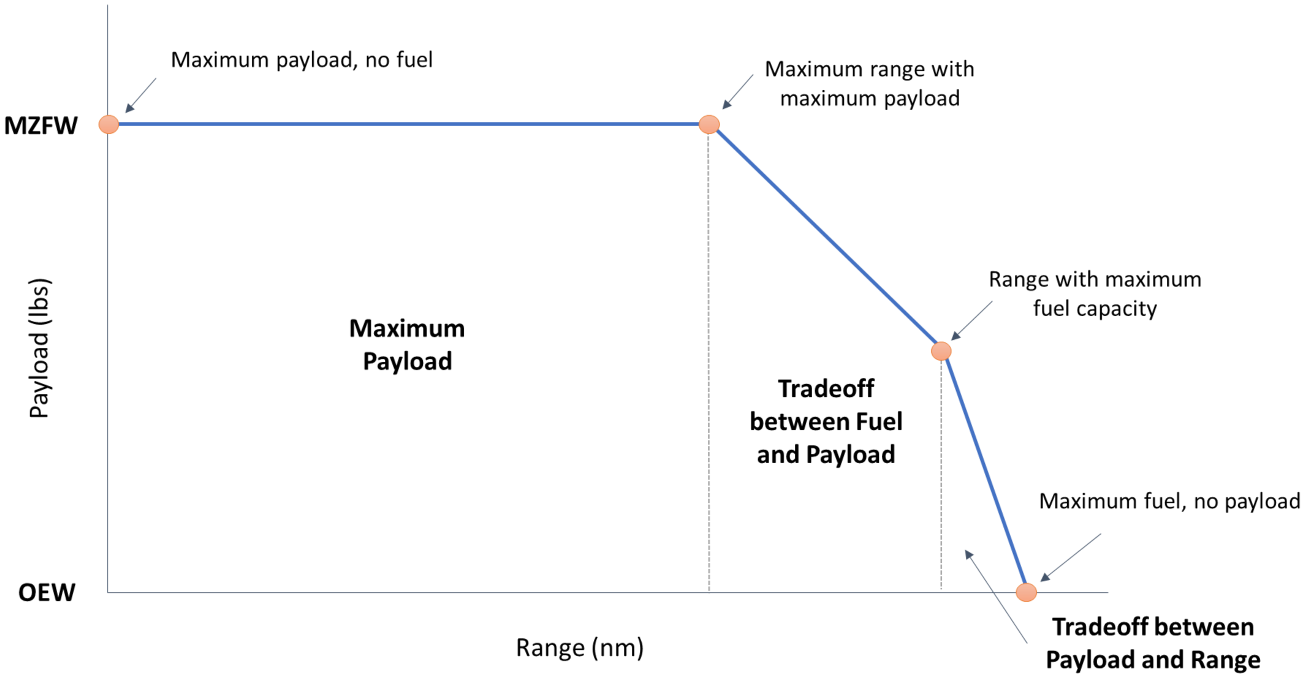


Figure 13.6. Payload–Range diagram.

Choosing the adequate relation between payload and fuel is an indispensable tool for optimizing the economics of an aircraft, complying with market requirements. In the payload-range diagram represented in Figure 13.6, it can be seen that flying a longer range means less payload to carry, which means, in turn, less profit for an airline. Airlines do not operate aircraft in the region of maximum fuel because it requires large reductions in the payload to achieve small increases in range and, thus, the profits decrease dramatically. For this reason, it is really important for an airline to operate aircraft nearly to its maximum range-MTOW capacities, adjusting its flight plans to these characteristics.

On their side, aircraft manufacturers have to offer a product line-up consistent with the needs of the market. In the Middle of the Market segment, operating aircraft should not have more than 5000 nm range and carry no more than 270 passengers to satisfy the needs of the airlines' routes.

The Boeing's approach of the market targets an aircraft of similar size of the 767 or the 757, carrying an approximate number of 250 passengers but with shorter range. The clue behind shortening the range of the aircraft resides in passenger comfort. Aircraft prepared to fly longer routes have to carry a big structure that holds the big amount of fuel needed for those routes. If that structure is no longer necessary because those routes are considerably shorter than the bigger models, the comfort of the passengers is bigger, and the cost is lower. Taking this into account, the new aircraft could be between the size of the single-aisle 757 and the 767, with a range of approximately 5000 nm, which would cover the gap left by the replacement of both aircraft.

13.2.2.4 MoM aircraft

This section aims to include an analysis of the current aircraft that are operating in the Middle of the Market sector, providing data about performance characteristics, range and capacity capabilities as well as orders and deliveries. However, due to its extension, this analysis has been included in Annex I at the end of the document although in this section it is included one case as an example.

As the MoM segment is not clearly defined, it is complicated to determine the aircraft competing in it. For that reason, the aircraft models analysed have been chosen to take as a base the data provided by Open Flights web page. With this data, it has been possible to define the MoM routes as well as the aircraft operating those routes. Chapter 13.2.4 provides a detailed explanation about routes analysis performed and the results obtained.

Figure 13.7 shows the aircraft that are currently operating in MoM routes, indicating the variants used and several relevant aspects related to their characteristics.

Figure 13.7: Current MoM aircraft

As it can be seen from the previous figure, as the Middle of the Market is located between the short-haul and long-haul markets, traditionally represented by single-aisles and twin-aisles respectively, models from both segments are used indistinctly for this type of routes. Therefore, selecting one model above another depending strongly on the airline's interests, resulting in a difficult quantification of this market. Consequently, there is not an aircraft model designed and optimised for these routes, so that several aircraft types absorb part of the MoM market share in different magnitudes. With the introduction of its new mid-size airplane, Boeing plans to change this situation.

However, as the analysis performed in Chapter 13.2.4 is based on routes data, it only considers aircraft with routes flown in 2018. As this study is focused on a market analysis for a time frame between 2020-2040, it is also required to take into account those aircraft models which have just entered the market or are expected to enter in service in the following years. Models such as the A330neo or B737 MAX are very recent, and they hardly have routes nowadays, but it is expected that this situation will change in the near future. It will be also necessary to consider fleet retirement since several of the aircraft shown in Figure 13.7 are old versions and it is very likely that some of them will not be longer in production in the period considered.

Several sources have been consulted to determine the potential competitors that could threaten the B797 market position between the 2020-2040 period. Within the single-aisle segment, the main candidate is the A321neoLR, a long-range variant of the A321neo with a range of 4000nm with which Airbus aims to compete in the MoM segment. As it is expected that the A321neoLR will be one of the most important competitors for the B797, its analysis has been included in this section.

Additionally, Airbus is considering modifying the A321LR by stretching it to absorb more market share from this sector. This variant is called A321XLR, which is expected to have a range of 4500nm, making it a direct competitor for the B797. From Boeing, it must be also considered the B737 MAX family, especially the MAX 8 y 10, whose order book is very promising with more than 2000 orders for both models. Although they have a lower range, it is very likely that they will be serious competitors for the MoM market, due to its efficiency and cost, which are commensurable with the A321neo. These two families, the A320neo y B737 MAX, will not only compete in the following years for the control of the single-aisle market but also they will try to absorb part of the MoM market.

Within the wide-body market, it is expected that the A330 neo versions will absorb part of the market in the next years, replacing the A330-200/300 fleet. However, the order book of one of them, the A330-800N, is extremely small and its perspectives are not very optimistic. For this reason, in the analysis, it is only included the A330-900N model, which is far more popular than the A330-800N.

On the other hand, the new version of the B777 current generation, the B777X will also be included in the analysis. It is planned to enter service around 2020 and, as the B777 has a significant market share, it is expected that part of this market will be absorbed by this model. The A350 and the B787 are aircraft relatively recent which still have several years of operational life. Due to this fact, they are considered for the analysis as they are expected to capture part of the MoM market share, but only the smallest versions, the A350-900, B787-8 and B787-9.

Finally, the B747 variants will not be included in the study as they are old models which are expected to be retired or replace in the following years. In addition, they are large aircraft whose range surpasses the target range studied. The B747-8, the re-engined version has not been considered a potential competitor due to its little commercial success and that it is focused on a more range market. The same reasons can be applied to the A380, that is, it is an aircraft of which objective is competing in long-haul routes and taking into account the announcement of its retirement, it is expected that the A380 will not be a relevant competitor and, for this reason, it has not been included in the analysis.

Table 13.2 summarises all the potential competitors considered in the study that could threaten the B797 market position in the 2020-2040 period as well as the aircraft, which currently operate the Middle of the Market segment. The table shows performance characteristics, dimensions and order book. In addition, in the Annex I located at the end of the document, it is included a detailed analysis of these aircraft, with data about routes flown as well as orders and deliveries. Moreover, Figure 13.8 shows a payload-range with the narrow-body and wide-body aircraft that are in service by both manufacturers at the present time, taking into account a two-class and a three-class configuration.

Aircraft model	*First Flight*	*Length (m)*	*Wingspan (m)*	*Range (nm)*	*Capacity (two-class configuration)*	*Maximum capacity*	*Total Orders*	*Total Deliveries*	*List price (USD millions)*
A319neo	2017	33.84	35.80	3700	120-150	160	35	0	101.5
A320neo	2014	37.57	35.80	3400	150-180	194	4143	641	110.6
A321neo	2016	44.51	35.80	3600	199	230			
A321neo LR	2018	44.51	35.80	4000	206	240	2327	184	129.5
A321XLR	2023	44.51	35.80	4500	206	240			
B737-800	1997	39.47	35.79	2935	160	189	4991	4979	102.2
B737-900ER	2000	42.11	35.79	2950	177	220	505	504	112.6
B737 MAX 8	2016	39.52	35.90	3550	178-193	210	2590	330	121.6
B737 MAX 10	2019	43.80	35.90	3300	188-204	230	579	0	134.9
A330-200	1997	58.82	60.30	7250	247	406	665	633	238.5
A330-300	1992	63.66	60.30	6350	277	440	789	765	264.2
A330-900N	2017	63.66	64	7200	277	440	240	11	296.4

1982/1998	*200: 47.3* *300: 54.4*	*38.05*	*3400-3915*	*200-243*	*239-295*	*1049*	*In service: 364*	*65-80*
1991	48.51	47.57	3900-6590	214	290	249	In service:13	160.2
1986	54.94	47.57	3900-5980	261	351	687	In service: 411	209.8
2009	57	60	7305	248	359	443	361	248.3
2013	63	60	7530	296	406	824	452	292.5
1988	70.66	64.40	7285	416	660	440	In service: 148	234
1994/1996	63.73	60.93	5240-7065	313	440	510	In service: 387	306.6
1997/2003	73.86	64.80	6030-7370	396	550	902	In service: 826	375.5
2020	69.8-76.7	71.80	7525-8690	365-414	-	344	0	410.2-442.2
2013	66.80	64.75	8100	315	440	713	257	317.4
2005	72.72	79.75	8000	575	853	290	237	445.6

Table 13.2: MoM aircraft characteristics

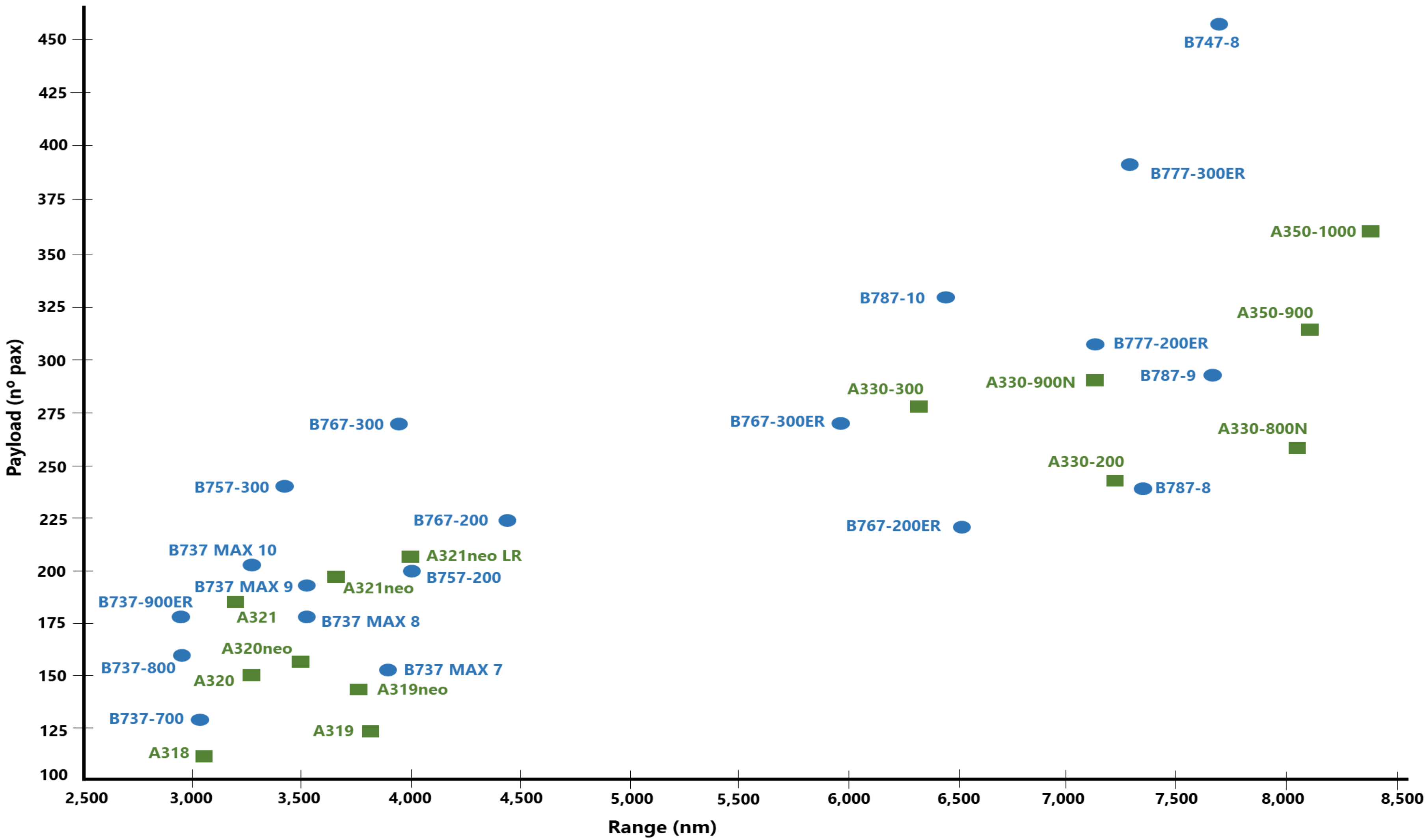


Figure 13.8. Payload-Range diagram considering two-class configuration

As it was said before, the Annex I located at the end of the document contains an analysis of the current aircraft that are operating in the MoM as well as the potential competitors which could absorb part of the MoM market share in the near future, with the following information about aircraft features and characteristics:

- In the first place, it is included a brief background with a description of main models, with characteristics such as the year of introduction, main features or commercial perspectives. The information has been extracted from the document written by The DVB Bank and Aviation Research, An Overview of Commercial Aircraft 2018-2019[4].
- A section with data about aircraft technical specifications and performance metrics. Different features relating to every aircraft are included such as range, capacity, dimensions, engines, etc. The goal of this section is to identify and summarize the performance differences between the aircraft that operate within the MoM sector as well as to present the data that will be used as inputs for the model cost developed in chapter 13.2.7. The information has been extracted from Airbus and Boeing web pages.
- The aircraft order book, in terms of deliveries and firm backlog. The order book serves to determine the aircraft with better commercial perspectives which could represent a threat for the new NMA. The information has been extracted from Airbus and Boeing web pages.
- Finally, a section with an analysis of the routes flown by these aircraft, which serves as a guide in order to determine the main aircraft which are used for MoM routes. Thanks to this analysis, it has been decided to include larger aircraft such as the A330 or the B787, as they have a significant percentage of their routes within the MoM category. For those aircraft which does not possess MoM routes due to its recent introduction, it has been included the routes flown from its previous versions.

The following section contains an analysis of the A321neoLR as an example, which includes all the previous parts mentioned. The rest of the models are analysed in Annex I.

A321-200N (NEO)/A321-200NX (NEO LR)

Background

The Airbus A321 is the largest member of the Airbus A320 family. It is a narrow-body, short to medium range, commercial passenger twin-engine jet airliner manufactured by Airbus. It entered service in 1994 and it was offered in two versions: the basic -100 and the longer-range -200 variant. The A321-200 was the first direct competitor to the Boeing 757-200. While not as range-capable as the Boeing 757-200, the A321-200 became a strong competitor on medium routes, such as US coast-to-coast.

In December 2010, Airbus launched the 'New Engine Option' (or “NEO”) for the A320 family. The baseline A320-200N (NEO) entered service in 2016 and the longer A321-200N followed in May 2017. These versions were re-engined with CFM International LEAP-1A or Pratt & Whitney PW1000G engines, which provide a 15% fuel burn advantage over their previous versions. With a backlog of around 2000 aircraft, the A321-200N is a very successful programme for Airbus.

In October 2014, Airbus revealed a new long-range variant of the A321neo. Initially, this version was unofficially called the A321neo LR. The new version will have a new door-configuration, called “Airbus Cabin Flex” (ACF) which results in up 20 more seats, bringing the total of passengers on an A321-200N to 240 (high density). As this new door arrangement is a structural change to the original A321’s fuselage, a new type certificate was needed, making it a new version of the A321-200N, called the A321-200NX.

This new version is clearly aimed at the 757-200 replacement market. It will have a range of 4000nm, 200nm more than the Boeing 757-200 (some of which are used on long-range trans-Atlantic routes) and 400nm more than the standard A321-200N. Intended markets are North America to Europe, Europe to Africa, North America to South America and S.E. Asia to Australia. With newer engines and more modern design, the A321-200NX will have 27% lower fuel burn than the 757-200. It is expected its introduction to the market in 2019.

Technical specifications and performance metrics

DIMENSIONS

Overall length	44.51 m
Wing span	35.80 m
Height	11.76 m

PERFORMANCE

Range (nm)	4000
Maximum take-off weight (Kg)	97000
Operating empty weight (Kg)	50100

CAPACITY

Typical seating	206 (two-class)
Max	240

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	828
Utilization (block hours per day)	11
Fuel consumption (Gallons per block hour)	1000

ENGINE DATA

SL thrust (ton)	14.05
Weight (Kg)	2380 Kg
Number of engines	2

Order book

As illustrated in Figure 13.9, the A321neo is a very successful programme, which has accumulated a great number of orders since its introduction. By December 2018, the A321neo has received 2075 orders, composed by 122 deliveries and a backlog of 1953. In spite of its recent introduction into the market, the perspectives of this model are very promising, as it has achieved to outsell its previous version, the A321ceo, as well as several models of the Boeing 737 MAX generation.

Orders	Deliveries	Backlog
2075	122	1953

Data as of December-2018

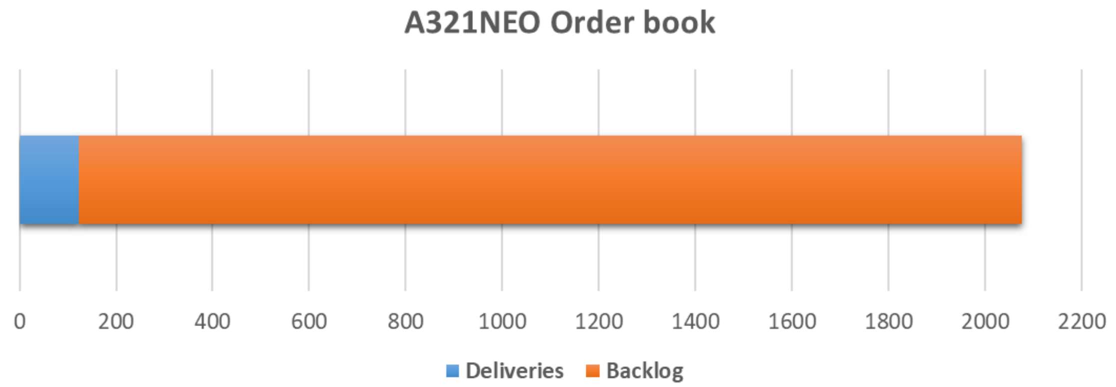


Figure 13.9. A321neo order book by December 2018

MoM routes analysis

The routes market share shown in Figure 13.10 belongs to the A321neo variant, which is expected to be the main competitor of the A320neo family for the Boeing NMA. In addition, it is the variant which is more used for MoM routes. As can be seen, almost 60% of the routes flown by this model are less than 1000 nm in length. The rest is distributed in the range between 1000 and 3000 nm, in such a way that as the distance increases, the number of routes is reduced. As of a length of 3000nm, there are no routes flown by the A321neo, although its maximum range corresponds to around 3600 nm.

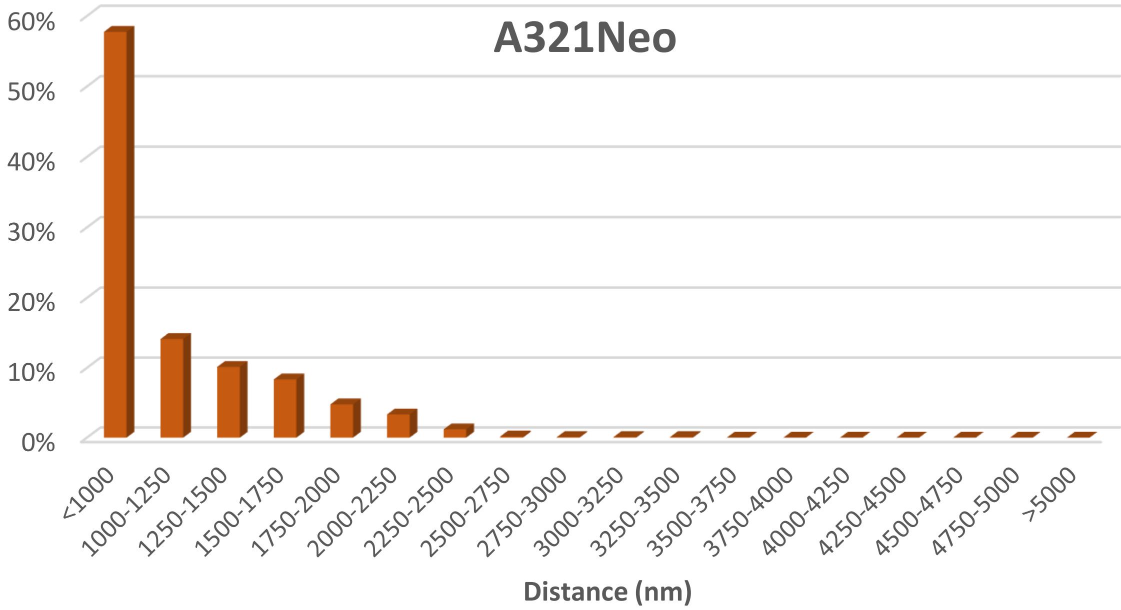


Figure 13.10. A321Neo routes market share

13.2.2.5 Is there an MMA market gap?

The MoM is certainly under discussion. Boeing claims that there is a clear gap of about 100 seats between the B737 and B787 that will be feed by the new Boeing 797; while Airbus argues that any MMA gap is covered by the A321neo and A330-900, and no new aircraft is needed, as the A321LR covers the market up to 240 seats and flies 4,000 nm and the A330-800 starts at 250 seats and flies more than 7,000 nm[5].

Then, which manufacturer is right? Is there an MMA gap or not? Is there a difference in how Airbus' and Boeing's product line-ups cover the market? Could the gap be that the present largest single-aisle, 737 MAX 9, stops at 220 seats and the next model, 787-8, starts at 240 seats? On the other hand, is the gap that the MAX 9 only flies 3,500nm and the 787 flies north of 7,300nm?

Figure 13.11 shows the Airbus and Boeing present product lines. Both cover the market with well-positioned aircraft, be it single-aisle or wide-body. Apparently overlapping coverage in seat capacity is reassuring.

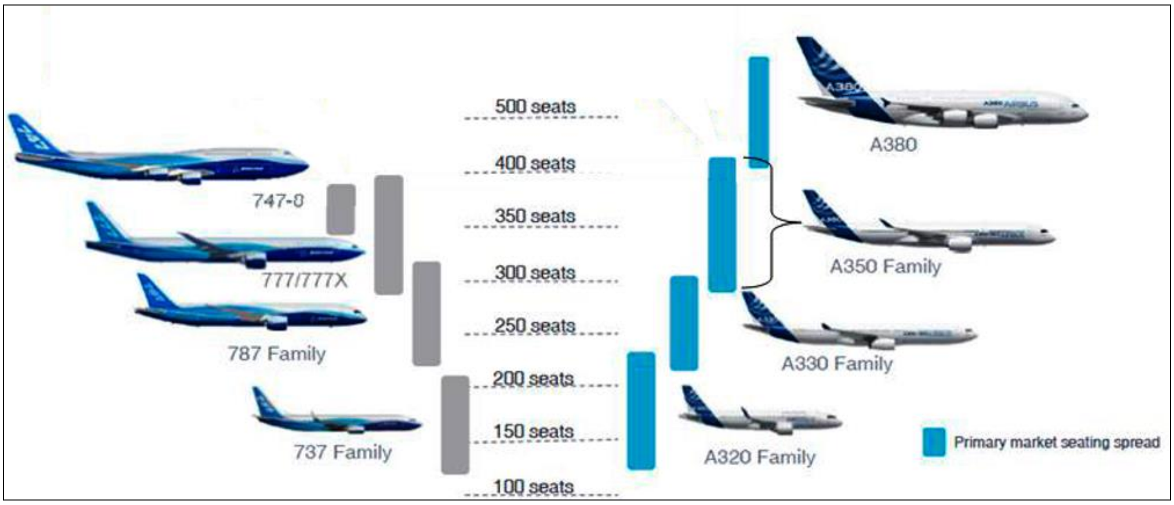


Figure 13.11. Boeing and Airbus line-up picture. Source: Airbus.

However, this simple and direct comparison is misleading, like comparing apples and oranges. The single-aisle aircraft are sold with domestic two-class cabins (180 seats for MAX 9 and 194 seats for A321neo) or even high-density cabins (220 seats for the MAX 9 and 240 seats for the A321LR). Wide-bodies are sold with long range two-class cabins, where business seats take up to three times the space of the equivalent single-aisle seat and weigh four times more. The different configurations are not directly comparable. Additionally, the range presented for each narrow or wide-body aircraft does not take into account the presented seat differences.

It is necessary to compare equivalent typical configurations, i.e. at an equivalent level of comfort, to really see the gap in the seat counts between narrow-body and wide-body. Only if all compared aircraft are equipped with the same seat standard, the true seat gaps surface. If a single-aisle aircraft is operated in long-range destinations, then a wide-body equivalent configuration should be considered for comparisons. A defined normalized long-range two-class configuration should keep:

- the same relationship between business class seats and economy class, of around 15% business of all seats;
- the same between business class seats and economy seats, around 15% business of all seats, so that all passengers, be it narrow-body or wide-body, can get their second meal before reaching the long-range destination; and
- the same number of passengers per lavatory.

With this normalized long-range two-class configuration the A330-800 and 787-8 hold around 240 seats, the A321LR can only hold 153 passengers instead of the 194 from the standard two-class and the B737 MAX 9 would house 142 seats.

Considering now a normalised single-aisle short-range high-density configuration, this case is the opposite extreme of the previous one. While it is true that in a bragging single-aisle high-density configuration Airbus boasts it can transport 240 people in an A321LR, this will be at the expense of a 28-inch pitch with slim line seat, and the 240 passengers sharing only three lavatories (i.e. 80 passengers per lavatory while the normal is 40). Applying the same level of comfort standard when packing an A330-800 or 787-8, would allow for much more passengers, up to 380 in the A330-800, and 420 in the 787-8. However, at these densities, none of the aircraft flies their advertised range. The A321LR stops at 3,300nm and the 787-8 at 6,000nm.

When comparing planes with the same comfort standards, is where the actual seat capacity gap in the market of around 100 seats can be really appreciated for both manufacturers' line-ups, give or take 10 seats. This gap doesn't change much if we measure with long-range, domestic or high-density rules. (See Figure 13.12)

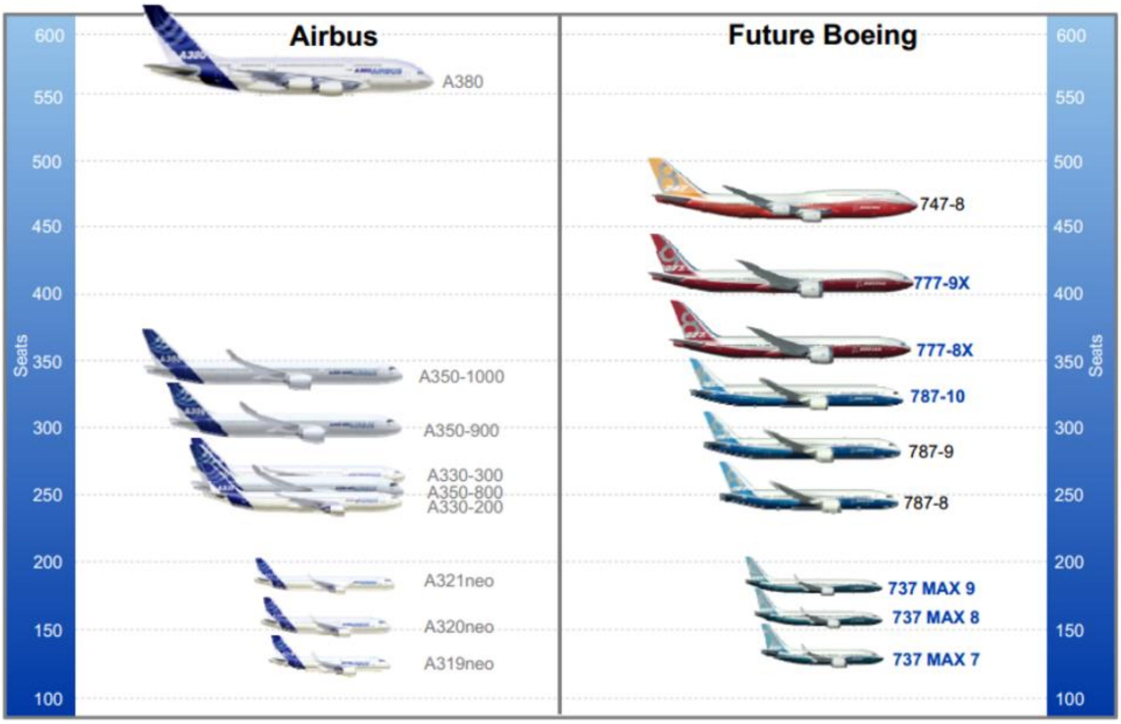


Figure 13.12. Products line-ups vs competition. Source: Boeing

Not only the definition but the size of the market is in dispute:

- Boeing says the market is between 2,000 and 4,000 aircraft over 20 years [6].
- Pratt & Whitney, Rolls-Royce and Leeham Co. estimate the market at between 2,000 to 2,500.
- Airbus sees the demand at about 2,000 airplanes, not enough to justify a new airplane [7].

13.2.3 Competition in the aerospace sector

The competition between Airbus and Boeing has been characterized as a duopoly in the large jet airliner market since the 1990s. The world aircraft industry today is increasingly controlled by Airbus and Boeing. The prize of this competition is the dominant position on a market in continuous growth. A total backlog of 14816 aircraft [8] is currently distributed mainly between the "Two Big" (Figure 13.13).

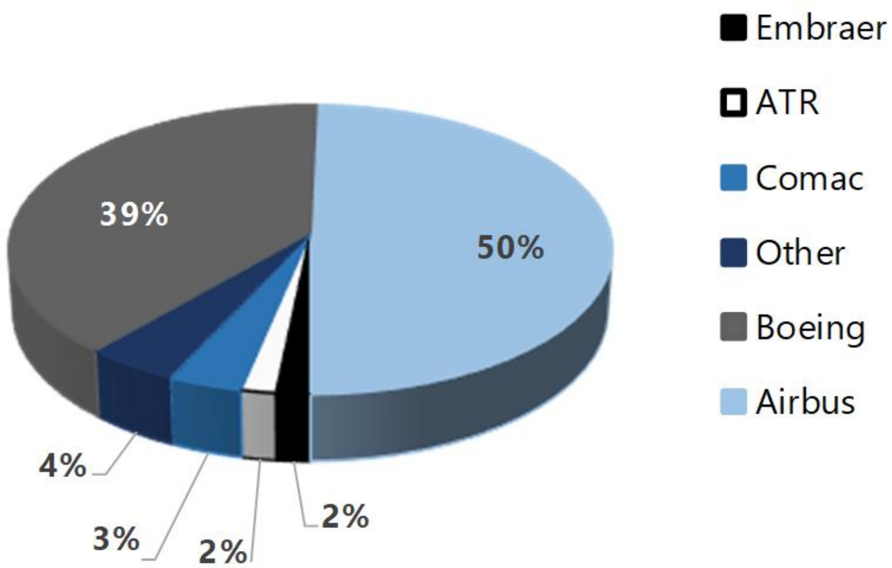


Figure 13.13. Commercial aircraft order backlog by the manufacturer.[8]

Large commercial jets are now about 60% of total industry output by value, not just at the final delivery level but through most of the component and structures supply chain, too. The reasons for this duopoly are multiple:

- Airbus and Boeing absorb a greater share of the industry. In 2018, Airbus acquired Bombardier's C Series with a new line of 110/130-seat jets, provisionally known as the A220-200 and A220-300. Boeing is creating a joint venture with Embraer covering Embraer's E-Jet series, spanning 75-120 seats.
- Extremely high entry barriers.
- Extreme concentration at the top of the market in terms of major revenue-producers.

History in jetliner competition is characterised by certain significant examples of competition between these two companies. Since the early '80s, every move of one competitor was mirrored by the other. As can be observed in Figure 13.14, nearly each of the airplane types in the portfolio of Boeing had, has and probably will have a counterpart in Airbus. Even if it does not show at present, A220 will not be alone on the graph, E-Jet will join.

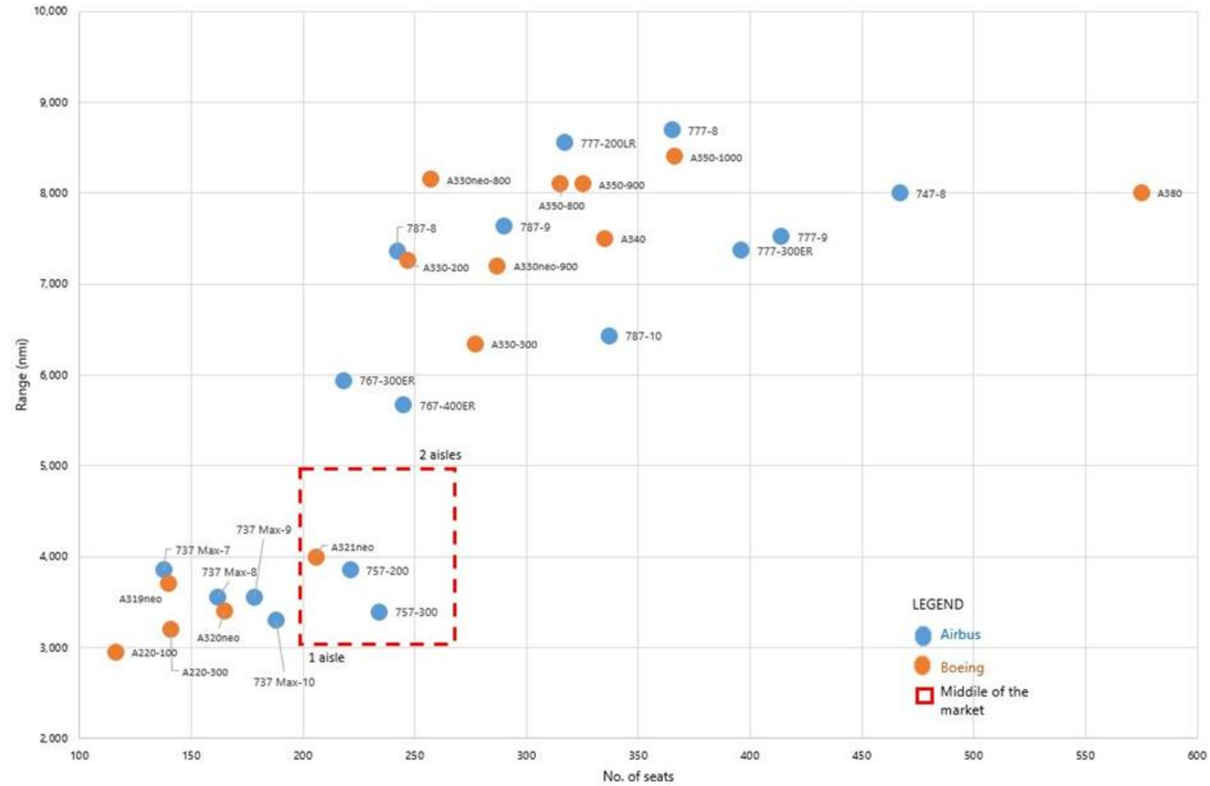


Figure 13.14. Boeing and Airbus payload-range diagram.[9]

A review of the Boeing and Airbus competition can bring hindsight of what was relevant for the dominance of the market in the past and might be also in the future. The most significant cases are outlined hereafter.

13.2.3.1 Analysis of the past Airbus/Boeing competition in the single-aisle market

Today's competition in the single-aisle segment is represented by Boeing's 737 and Airbus's A320 families. Some consultants estimate that the segment "generates a vast majority of the profits" for each of the airframes; as they represent the bulk of the historic volumes delivered (around 10,500 for Boeing and 8,500 for Airbus) and of the existing orders (4,763 for Boeing and 6,536 for Airbus), according to the data provided by manufacturers [10][11]. However, as shown by the data in Table 13.3, the order rush seems to have decelerated in 2018.

Model	Deliveries		Net orders		Backlog 2018
	2018	2018/2017	2018	2018/2017	
A220	20	n/a	135	n/a	480
A320ceo	240	63.7%	10	7.8%	165
A320neo	386	213.3%	531	57.3%	5,981
Total Airbus	646		676		6536
737NG	324	n/a	-24	n/a	88
737 Max	256	56.3%	699	53.3%	4,675
Total Boeing	580		675		4763

Table 13.3. Airbus and Boeing 2018 orders. [10][11] [12]

Both companies still keep a BB ratio (book-to-bill ratio, the ratio of orders received to the amount billed for a specific year) at a value higher than 1, which is characteristic of a boom period. In addition, the table shows that B737 and A320 families, with their latest versions, are the models with a higher backlog, illustrating the success of the single-aisle segment.

Historically, Boeing's 737 first entered service in 1968. A variety of derivative aircraft based on the initial design, with different ranges and seating capacities, have been produced over the years. Airbus, after being successful with A300 series, planned its narrow-body family starting in 1978 as jet 1 and jet 2, a project targeted to compete with B737 and DC-9, the uncontested leaders of the market at the time [9]. The engineering capacity freed by the completion of the first project (A300) was put to work for the second.

The consortium introduced its A320 family into service in 1988. It was the first airliner conceived with fly-by-wire controls. The aircraft's fuselage has been stretched and shrunken to fill different market niches with the introduction of the A321, A319, and A318. A variety of engines have been used on the Airbus airplanes allowing for incremental improvements in fuel efficiency. As an answer, Boeing launched the members of the Next Generation 737 family in the late 1990s and early 2000s with updated engines, cabin interiors, and flight deck avionics as well as winglets and changes to the airframe.

Categorically, within the vintage generation, the Boeing 737-600 competes directly with the A318; the Boeing 737-700 competes directly with the A319; the Boeing 737-800 competes directly with the A320, and the Boeing 737-900 competes directly with the A321. The battle between both companies continued with the introduction of the Airbus Neo generation and the Boeing MAX generation. On the one hand, the 737 MAX series is offered in four lengths, typically configured for 138 to 230 seats and a 5,954 to 7,084 km range (it does not mean that one type's version is able to transport the maximum number of passengers to the maximum range, on the contrary). The 737 MAX 7, MAX 8 and MAX 9 replace, respectively, the 737-700, -800 and -900. Additional length is offered with the further stretched 737 MAX 10 (scheduled to be delivered from 2020). On the other hand, Airbus Neo series is offered in three variants, which are based on the previous A319, A320 and A321. The passenger capacity varies between 140 to 244 seats and a range of up to 7,400 km (Table 13.4).

Model	No of seats	MTOW (t)	Range (nm)	List Price (MUSD)
A220-100	116	60.80	2,950	79.5
A220-300	141	67.60	3,200	89.5
737 MAX 7	138	80.30	3,850	96.0
A319neo	140	75.50	3,700	101.5
737 MAX 8	162	82.19	3,550	117.1
A320neo	165	79.00	3,400	110.6
737 MAX 9	178	88.31	3,550	120.2
737 MAX 10	188	92.00	3,300	129.9
A321neo	206	97.00	4,000	129.5

Table 13.4. Narrow-body current market

The list prices for two competing models belonging to rival families are comparable and the discount policies of both companies are similar (sometimes even 50-60% discount on the list price [13]).

In today's aerospace market, the MAX and the Neo are the best-selling products for both manufacturers. These models are more fuel-efficient, longer-ranged, enhanced passenger interior and enhanced passenger comfort than previous B737/A320 families, both of which have sold very well since their introductions. A comparison of the evolution of the order backlogs for each of the competing families as per September 2018 is shown in Figure 13.15.

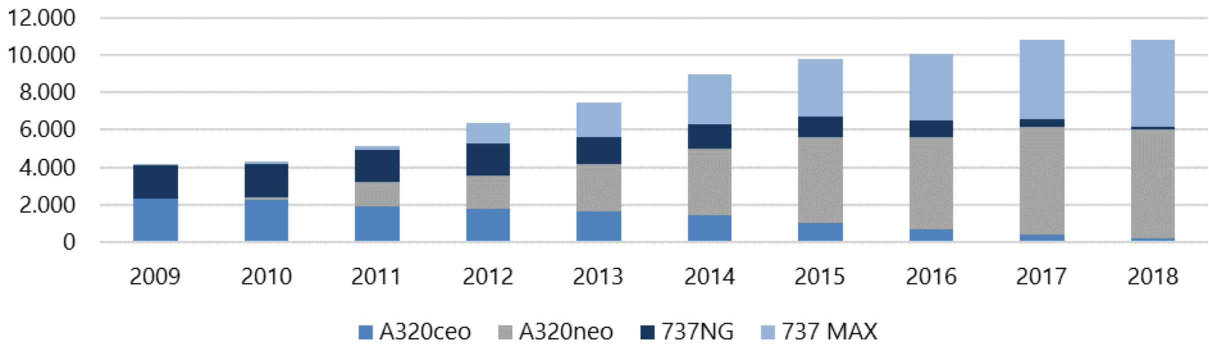


Figure 13.15. Evolution of order backlogs. [14]

From this representation, it can be easily understood that the attraction of the new generations (3rd for Boeing and 2nd for Airbus) was causing the slow extinction of the previous one and that Airbus managed to absorb a larger proportion of the market demand growth. Comparing both families in terms of total orders, Airbus rules the market of re-engined single-aisle, with 60% of the market. It is certainly possible that Airbus will maintain the 60-40 advantage in the following years, but this scenario may change in the upcoming years.

13.2.3.2 Analysis of the past Airbus/Boeing competition in the wide-body market

A wide-body aircraft is a jet airliner characterised by the following features: two passenger aisles, a fuselage diameter of 5 to 6 m and a total capacity, which can vary between 200 to 850 passengers. Wide-body commercial aircraft manufacturers have experienced fierce oligopolistic competition due to the small number of market participants and their high durability, high start-up costs, and long production runs. Four major aircraft manufacturers (Boeing, Airbus, McDonnell-Douglas and Lockheed) competed for the market in 1970-80s without any new entrants. Lockheed exited the market after experiencing economic problems and a big drop in sales in 1984. The demand for the type was discouraged by the price superior to the competition's, while its costs were too high to promise a pertinent profit, and the losses incurred by the late completion of RB 211 engine development by Rolls-Royce could hardly be recovered [23]. Consequently, Lockheed decided to stick to the military market on which they had and still have a dominant position. After McDonell-Douglas merged with Boeing in 1997, the wide-body aircraft market became a duopoly between Boeing and Airbus.

The wide-body age began in 1970 with the entry into service of the first wide-body airliner, the four-engined, partial double-deck Boeing 747. New wide-body aircraft soon followed, including Lockheed L-1011 TriStar entered in service after important delays also in 1970 and the McDonnell Douglas DC-10 entering service in 1971. All three types had either 3 or 4 engines, a must for transoceanic flights in an era when ETPOS was not yet permitted by the power plants reliability levels. Then, the first wide-body twinjet, the Airbus A300, entered service in 1974.

After the success of the early wide-body aircraft, several subsequent twin designs came to market over the next two decades, including the Boeing 767 and 777, the Airbus A330 and A340, and the McDonnell-Douglas MD-11. In the "jumbo" category, the capacity of the Boeing 747 was not surpassed until the A380 appearance, both of them having four engines. This category seems to have become out of fashion, due mainly to lower economics compared with big twins. Consequently, B747-8 proved to be a commercial failure, while A380 followed suite, ending with its production discontinued (announced on February 14th, 2019 [15]), much earlier than the sales volumes could approach the break-even point.

In the mid-2000s, rising oil costs caused airlines to look towards newer and more fuel-efficient aircraft. Two such examples are the Boeing 787 Dreamliner and Airbus A350 XWB, both featuring a largely (about 50%) composite structure and modernised, low consumption, power plants. The current offer on this market is shown in Table 13.5.

Model	No of seats	MTOW (t)	Range (nm)	List Price (MUSD)
787-8	242	227.95	7,355	239
A330-800	257	251	8,150	259.9
A330-900	287	251	7,200	296.4
787-9	290	254	7,635	281.6
A350-900	325	280	8,100	317.4
787-10	330	254	6,430	325.8
777X-8	365	351.5	8,690	394.9

Model	No of seats	MTOW (t)	Range (nm)	List Price (MUSD)
A350-1000	366	316	8,400	366.5
777X-9	414	351.5	7,525	425.8
747-8	410	447.7	8,000	402.9
A380	575	575	8,000	445.6

Table 13.5. Wide-body current market

The same remark can be made as in the case of the single-aisle airliners: large discounts are arranged with special customers. The total backlog for wide bodies (as per August 2018) was 2318 airplanes, with the market shares of each type shown in Figure 13.16.

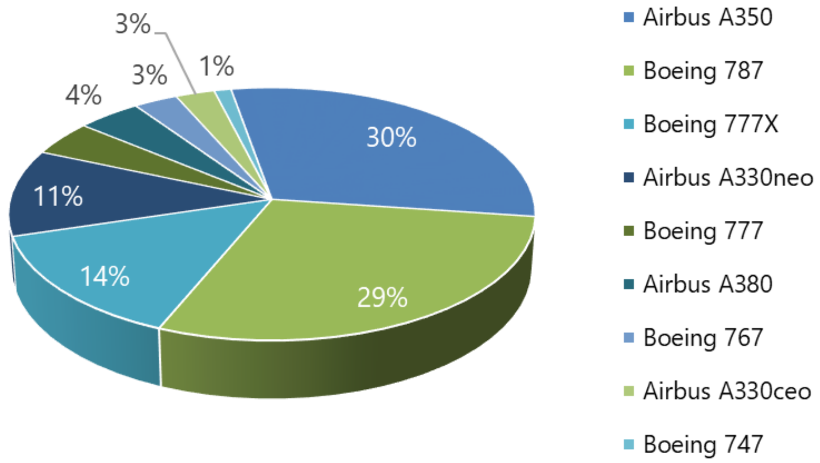


Figure 13.16. Wide bodies order backlog market share.[14]

The most recent backlog/deliveries evolution for each competitor on this market is shown in Table 13.6.

Model	Deliveries		Net orders		Backlog 2018
	2018	2018/2017	2018	2018/2017	
A330ceo	46	68.7%	9	60.0%	60
A330neo	3	n/a	18	300.0%	235
A350	93	119.2%	40	111.1%	659
A380	12	80.0%	4	-200.0%	87
Total Airbus	154		71		1041
747	6	8.1%	18	2.6%	24
767	27	192.9%	40	-2000.0%	111
777	48	480.0%	51	340.0%	105
777X	0	n/a	0	n/a	326
787	145	n/a	109	116.0%	622
Total	226		218		1188

Table 13.6. 2018 backlog/deliveries

The BB ratio (book-to-bill ratio) is less than 0.5 for Airbus while for Boeing is a little better, close but still under 1. A BB less than one might signal a certain reluctance of the airlines to commit to higher capacities.

Today, the market for large wide-body aircraft is split between Boeing and Airbus, each with 60-40% of the market, depending on the year. This market duopoly means that Boeing and Airbus are constantly fighting to gain an advantage over the other in terms of aircraft sales. Before a new contender (for example, the CR929) would come with a tempting offer, this situation will persist many years from now.

13.2.3.3 Analysis of the past Airbus/Boeing competition in the MoM

As was discussed in Section 13.2.2, the Middle of the Market segment definition is not clear and may be different depending on the manufacturer. Generally, it is defined as a mid-size segment, located between the narrow-body and the wide-body market, and which encompasses aircraft carrying 200 to 270 passengers and a range that can vary from 3,000 nm to 5,000 nm, as defined by Boeing executives [16]. Due to the poor definition of this market, some aircraft that are found in the limit can be considered or not a part of this market, such as the A321neo or some variants of the 737 family. However, the main aircraft that have represented the competition within this market until the date is the B757/B767 from Boeing and the A330 from Airbus, taking into account their different variants.

On the one hand, the 757 was a twin jet airliner that was produced by Boeing from 1982 to 2005[17]. It was a narrow-body airliner with the normal configuration being three seats on either side of a single-aisle. Boeing designed the 757 alongside and slightly behind the Boeing 767. The 767, which is a wide-body airliner, and the 757 share many of the same design features in airframe as well as internal systems. In late 2003, Boeing decided to end 757 productions because the increased capabilities of the newest 737s and the new 787 fulfilled market's needs, however, some airlines keep these aircraft on operation but most of them are being replaced. According to Flight Fleet Analyser database, as per July 2018, a number of 667 units of B757 (611 units of -200 and 56 of -300) are still in service with airline operators[14]. The 767 is still in production but the number of deliveries has been reduced in recent years and, as per February 2019, the 120 units of backlog consists only of freighter (UPS and FedEx customers) and military (tanker) versions[18]. In addition, due to its' old design, most of these aircraft have a high average age, surpassing twenty years in some cases. For this reason, one of the main objectives of the new Boeing MoM aircraft is serving as a replacement for the 757/767 fleet.

On the other hand, the main competitor of the 757/767 is the Airbus A330. The Airbus A330 is a large-capacity, wide-body, twin-engine, medium to long-range commercial passenger airliner, which was conceived in the late 80s (first flight in 1997). Versions of the A330 have a range of 4000 to 7,250 nm and can accommodate up to 345 to 400 passengers in a two-class layout. The A330 was developed in parallel with the four-engine A340, which shared many common airframe components but differed in the number of engines. Since its launch, the A330 has allowed Airbus to expand market share in wide-body airliners, competing with Boeing aircraft such as the 767, 777 and even the 787. Because it is also an old design, Airbus offers a replacement of the current A330 (referred to as the A330ceo) with the A330neo, which includes new engines and other improvements.

Due to its performance improvements and flexibility, the A330neo is considered as a strong candidate for replacing the ageing fleet of Boeing 757/767's. However, as per November 2018, the backlog for A330neo was of only 224 units, all of them for -900 neo, none for the proposed longer-range

800neo[18]. In the meanwhile, Boeing does not have a clear candidate to replace the 757/767 fleet, which may lead in the coming years to drop-in orders in favour of Airbus. It is possible that the new Boeing MoM aircraft change this scenario if its introduction to the market is not delayed and it offers performance advantages versus its competitors. A good promise is the capability of A321neoLR to cover the MoM segment. It still enjoys a good growing potential (the composite wing in A321neo-plus exercise). Its demonstrated current range is over 4000nm and its maximum capacity has still potential to be increased from the existing 206 seats to perhaps 250. B737Max lacks this stretch potential.

A clean-sheet design of the MoM would be a premiere at Boeing for the last 2 decades. Their commercial aircraft subsidiary seems to have preferred upgrading older models, a conservative strategy. A state-of-the-art solution for MoM is supposed to contain composite wing and fuselage, a hybrid cross-section and next-generation engines [16], everything promising a low $/seat/nm index. If all this can be achieved at a reasonable list price, it can be a winner in its market.

The size of the market is estimated by different analysts between 2000 units and 4000 units[19], but the window of opportunity is not extended beyond 2030, in view of the need of the airlines to replace the existing MoM fleet.

13.2.3.4 Summary of relevant competition factors in the past that might be also in the future

The continuing Boeing-Airbus rivalry has been in place during decades, since Boeing began, in the late 80s and early 90s, to take seriously the challenge of the small outsider just established in 1970. The only notable competitor at that moment for Boeing on the commercial airliner market was McDonnell Douglas, manufacturer of both narrow bodies and wide bodies. But McDonnel was strongly affected by the recession in the early 90s and was to be merged into Boeing in 1997. Therefore, instead of Boeing becoming a monopoly on that market, it was irritated by the appearance of the unexpected European competitor. Some analysts even consider that the Airbus presence on the market accelerated the decline of McDonnel and its absorption by Boeing[20]. For a better understanding of the development circumstances of the duopoly, a short review of the conditions in the industry is provided.

The significant achievements in aerospace industry (and here the airliners production is relevant) are based on three ingredients:

1. **Strong financials:** it is well beyond the possibilities of a normal size company to spend the multi-billion dollars necessary to develop a new type of airliner. Producing such machines is an act of large-scale economics, so it needs to be supported, more or less explicitly, by governments. This happens mainly because the private capital is reluctant to approach very large investment with a rather long recovery horizon (they prefer early repayment profiles)[20]. The capital markets are also less inclined to take the risk of failed projects and assume its painful consequences.
2. **Powerful science and engineering resources:** resources that need to be based on an existing wide base of STEM (Science, Technology, Engineering, Mathematics) education output, on a systematic experience accumulated in any of the contributing fields, as well as on a good capability of invention and innovation.
3. **Efficient industrial organisation:** developing a product means also proper industrialisation. Reaching appropriate production volumes at competitive costs and quality levels to satisfy the

market demand is probably the most difficult task. It requires a rather rich experience, a strong discipline, a quality approach well implemented, a science of managing a large supply chain. Every such component of the industrial system needs to be built and maintained using a careful design and proof process.

The absence of any single one of these three ingredients in the minimum necessary amount is spoiling any chance of contemplating the entrance on this market. This means that high entry barrier prevents outsiders to threat the incumbents' positions.

After the end of WW2, the complete package of the three ingredients listed above was present (at the then necessary levels) in a small and select group of countries: the UK, the US, France, USSR, Netherland. During the ensuing decade, they developed airliners based on the acquired expertise in large bombers or military transports but being able to incorporate new revolutionary technologies as the turbine propulsion. However, in time, probably starting in the mid-50s, larger projects (B 707 and DC8 jets and Tu 114 turboprop) began to require huge sums, which hardly could be available to smaller players compared to the US and the USSR. UK tried to stay in competition with Vickers VC10 but soon abandoned, limiting the effort to smaller sized BAC111[9]. France also kept a modest ambition with Caravelle while Netherland (with German contribution) launched Fokker family. Besides UK, France and Netherland, other European countries like Italy, Spain, Germany enjoyed valuable engineering and industrial resources (ingredients 2 and 3 above) but, obviously, lacked the finance potential necessary to grand aviation projects.

One decade later, in the mid-60s, Europe began to resent the advance US and USSR were gradually acquiring in the aeronautical industry. The European leaders understood that, as an aggregate, Europe had plenty of engineering brains and industrial expertise, so the lack of individual national financing potential was the only obstacle to proceed to large projects. The solution was an alliance of European nations to establish an entity able to compete on the large aircraft market. Appropriately recorded as "*Groupement d'Interet Economique*" (GIE), Airbus consortium was set up in December 1970 by France (Aerospatiale), Germany (MBB and VFW Fokker), UK (British Aerospace), Spain (CASA) and Netherland (Fokker VFW). Financing was provided by loans from French, German, Dutch and Spanish governments, from a consortium of French and German banks and from private BAe funds [9]. At that time, the partners had already started work for the first twin-engine wide-body airliner, A300, featuring some new technologies like composite structural elements. Entering service in 1974, it proved to be a success, competing in the so-called "wide-bodies war" against the three contemporary US machines, B757, DC-10 and L-1011.

At present, as it was mentioned before, the market is dominated by the two rival giants. Any tentative to steal a fraction of the market from the Big Two by an outsider not strong enough in all three ingredients is doomed (as the case of Bombardier, despite the active support of the Canadian government). Interesting evolutions to follow during the next decade would be the technical and commercial success of the Chinese narrow-body C919 and of China-Russia wide-body project CR929. The last one seems to have all the ingredients provided by the project partners, but it will have to struggle against the power of established brands.

Considering the MoM business case, from the point of view of the three ingredients, Boeing's decision is very difficult and presents the following obstacles:

- Boeing can definitely procure the $10-15bn financing representing the estimated cost of the development. However, the size of the market is great uncertainty, so is the return on investment, depending on the total volumes sold. Reaching 4,000 units produced during the life cycle of the model seems rather optimistic that the current wide-body fleets do not record any model numbering over 2,000.
- The industrial capacity is another uncertainty for Boeing, although at a smaller scale than the other two Ingredients. At this moment, their production capacity is quite stretched by their huge efforts to ramp-up production for the existing types and to introduce the new 777X [14][18], approaching completion of the development phase. A need to extend the production capacity to accommodate MoM aircraft might occur after 5-6 years when the production levels are, hopefully, stabilised.
- Probably critical in the decision is engineering capacity. For the moment, huge Boeing resources are involved in 777X. They will not be available for other jobs before 2020, which might jeopardise the chances of the MoM aircraft to catch the window of opportunity mentioned before. This is why hope for the project's eventual go-ahead is seen in the Embraer merger which might bring new engineering resources (besides a new market extension).

Consequently, the MoM decision, expected for 2019 was explicitly postponed for 2020 by Boeing executives, an announcement made this January [21].

Finally, it is worth to mention that in the recent history of the industry there are several relevant factors and lessons learned that can be extracted and that should be considered in the future in order to maintain competitiveness in the market. Here are some examples:

Competition between the two producers. A duopoly is a market situation in which only two producers exist. The decisions and actions of one producer affect and are affected by the decisions and actions of the other producer. An example of this situation is reflected in the Airbus/Boeing duopoly, in which both companies have maintained an aggressive competition over time. As a result, manufacturers must pay close attention to the actions and reactions of its competitor as well as to respond to each other's moves to prevent an inferior aircraft in a market segment from losing market share and profit potential. This scenario generally fosters relatively high innovation, high production and low prices in order to maintain an advantage in the market. However, there is also the risk that both producers may collude explicitly or tacitly or reach an agreement in order to reduce their risks for investment and new product development.

Price competition. Due to the intense competition within the sector, it is quite usual that companies such as Airbus and Boeing apply price discounts in their products to gain more market share. This is especially applied for the commercial launch of a new airplane in order to get more orders from airlines. In fact, both companies have accused each other several times of carrying out this type of practices. However, price war hurts the profits of all the companies in a well-established industry and, for that reason, companies should avoid it.

Innovation. Innovation is a key factor that has been used by Boeing and Airbus in their strategies to achieve success, which has enabled both companies to develop products that attract very high demand in the market. Innovation normally implies the use of advanced technologies to develop new products with the objective of seeking performance advantages in their products. Developing modern technologies is a very positive factor that helps to advance the industry, allowing to obtain more modern and efficient aircraft. As an example, the Boeing 787 Dreamliner was the first large airliner to use composites for most of its construction.

Commitment to deliveries. In the industry, there have been cases in which manufacturers have been unable to comply with promises made regarding aircraft deliveries. An example is the Airbus A380 case, a superjumbo jet which has received to date 331 firm orders. This aircraft had several delivery delays that caused dismay from its buyers as well as a drop in the earnings expected. In addition, Airbus had to negotiate compensation with its customers for postponing deliveries. Therefore, to be able to fulfil delivery commitments is an important factor as, in case of not achieving it, it would lead to disappointment and distrust of the company.

Customer-oriented strategies to reach success. Both Boeing and Airbus carefully research customer needs and strive to satisfy these needs since they represent a competitive and successful factor for a company. In addition, the airplane purchasing decision criteria of airlines includes not only load and range factors and operating costs but also passenger comfort. Airbus has been quite competitive and successful in recent years as a result of developing a clear empathy with its customers, encouraging a two-way flow of views, ideas and technical feedback on its aircraft in service around the world.

At present, Boeing and Airbus appear equally competitive. Both companies must understand their customer’s needs and buying behaviour, anticipate how customers’ needs will evolve over time, keep a close eye on the competition, be innovative in creating customer value, and strive to deliver total customer satisfaction. The company that can consistently and efficiently do all of these will be the winner at the end.

13.2.4 Middle of the Market routes and fleet analysis

In this chapter, an insight over the main scheduled air routes in 2018 is provided, focusing on those on the range from 2500 nm to 4500 nm, which are the objective routes of the Middle of the Market aircraft. The data-set used for this analysis has been extracted from the open-source OpenFlights.org [22] database, which recovers data from airlines, airports, aircraft and scheduled air routes from commercial carriers with:

- Over 33,000 international and domestic air routes updated up to December 2018.
- Around 5,800 air carriers.
- Over 10,000 airports.
- More than 130 commercial aircraft models.

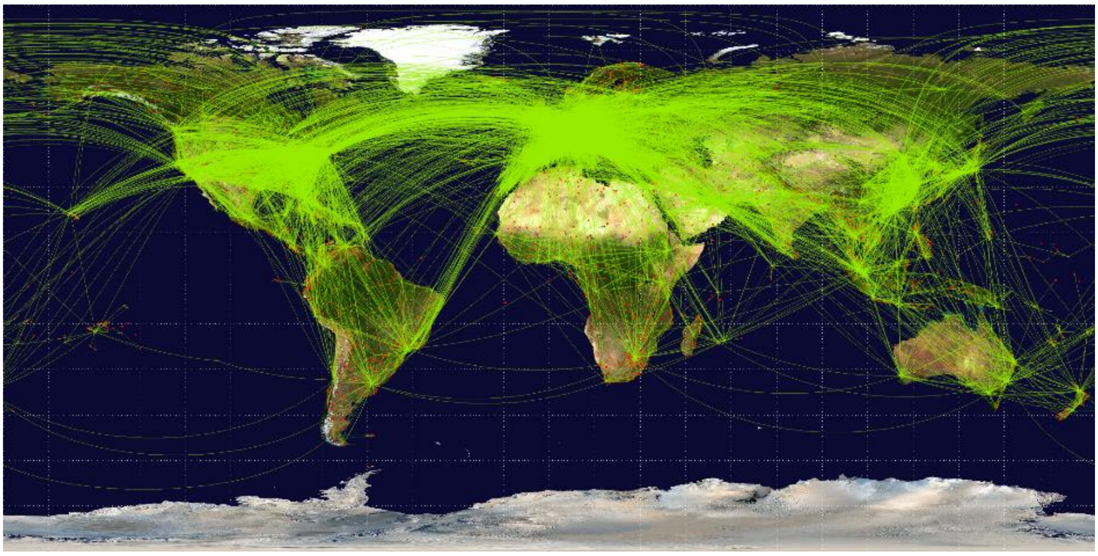


Figure 13.17. Open Flights routes over the world's map. [22]

Although the database does not provide traffic volumes (RPKs), the analysis of this data gives valuable information about the busiest flows between regions, represented by the number of routes connecting a certain pair of countries. If two regions hold a big number of routes between their cities, it means that there is an important passenger flow between those two regions and, consequently, a big number of flights and required aircraft to connect these areas. The same argument can be used to discuss the aircraft share of the market. If an aircraft holds a big number of air routes, it can be translated to a big market share percentage of that aircraft, within the considered market segment.

In this chapter, firstly, a summary of the most transited routes within the Middle of the Market will be presented, in order to identify the regions of the world with the highest share of this market and the most important flows within the considered range. Secondly, an analysis of the most used aircraft and the average stage length of each model is presented in section 13.2.4.2, in order to identify how passenger airlines, operate each aircraft. Finally, a market share estimation based on the analysed data is presented in the last section, showing the percentage of routes covered by every aircraft model in the analysed range, by segments of 500 nm.

13.2.4.1 Passenger flows in the Middle of the Market

This section will provide insight over the routes that are flown by the Middle of the Market aircraft, described in Section 13.2.2. First, the methodology of how PARE has segmented the air routes according to its distance is presented, highlighting the main differences between different airlines or organizations. After it, the results of the data analysis will be presented.

Medium-haul routes definition

There are plenty of different opinions regarding flight length and air routes categorization. Depending on the operator, organization or aircraft manufacturer, air routes can be divided into short-haul, medium-haul or long-haul according to flight distance, although the boundaries between each of them are not very clear.

In Europe, Eurocontrol [23] defines short-haul routes as those shorter than 1,500 km (930 mi; 810 nm), medium-haul between 1,500 and 4,000 km (810 and 2,160 nm) and long-haul routes as longer than 4,000km (2,200 nm). On the other hand, Air France [24], defines short-haul as domestic, medium-haul as within Europe/North Africa and long haul as the rest of the world.

American Airlines [25] define short-/medium-haul flights as being less than 3,000 mi (2,600 nm) and long-haul as either being more than 3,000 mi (2,600 nm) or being the New York–Los Angeles and New York–San Francisco routes.

The definition of the route depends a lot on the business model of the airline, the operations and the region where it is placed. Nevertheless, for the purpose of this study case, it is necessary to focus on a different categorization, taking into account aircraft capabilities. For this purpose, PARE will adopt its own categorization in order to distinguish the Middle of the Market potential routes from the others, according to the proposed range of the new concept B797. Thus, the following categorization will be used:

- **Short haul:** Routes no longer than 2,500 nm, which represent nowadays the biggest part of the worldwide air traffic. These are the routes mainly flown by regional jets (such as Embraer ERJ-family or Bombardier CSeries), and medium-sized single-aisles such as Boeing 737 and Airbus A320.

- **Medium haul:** Routes between 2,500 and 4,500 nm. That is the objective mission of the new proposed Boeing 797. This market is nowadays mainly operated by long-range and medium to large size wide-body aircraft such as the A330, the Boeing 777 or the Boeing 787, as well as the two current MoM Boeing aircraft, the 757 and the 767. The lower bound of this sector is also operated by single-aisle shorter airplanes like the B737 or the A320.

- **Long-haul:** Those routes longer than 4,500 nm, operated mainly by bigger wide-body aircraft such as the A350, Boeing 777, Boeing 787 or the A380.

The medium-haul traffic is the target of the future Middle of the Market aircraft production, since it represents about a 20% of the total worldwide traffic, and a big number of the aircraft to be produced will be used to operate in this market.

Middle of the market flows

In the 1980s, the air transport was mostly extended over Europe and North America, with North America dominating the aircraft production market and with big jets such as the Boeing 747 crossing the Atlantic. A big percentage of the routes that nowadays can be considered as 'MoM' were connecting Europe to North America. The concept of the Middle of the Market started then, and Boeing introduced a new concept of aircraft optimized for these transatlantic routes: The Boeing 757 and the 767, motivated by these connections between Europe and the US. The Middle of the Market was almost exclusive of transatlantic flights and until the entry into service of the 767 and the 757 it had been operated mostly by 4-engined jumbos and other big wide-body aircraft. The air transport has changed since then, and more routes are being opened constantly, connecting a wide number of city pairs all over the world.

The average distance of a flight from the capitals of the Western Europe countries of Europe (i.e. Paris, London, Madrid, Berlin or Rome) to NY is between 3000-3500 nm, and to China (i.e. Shanghai or Pekin) rounds 4500 nm, which are the most important pairs between EU and the US, and it is inside the range used to describe the MoM. To get an idea of which places can be reached within this sector, both circles of 2500 and 4500 nm centred in Brussels (Belgium) have been drawn in the following figure.

Figure 13.18. Mid-haul routes scope from Brussels (Belgium)

Nowadays, the biggest number of scheduled mid-haul flights still corresponds to pairs between North American and European cities, but in addition to that, there is a big number of routes within China and the US, and within Europe and South/Central America, with Spain as the hub of these connections. Additionally, an important market exists in the air routes crossing the Pacific Ocean and connecting countries like Japan and the US.

The *OpenFlights* database accounts for more than 2000 routes in the Middle of the Market segment. As said, the main routes connect European cities with the US and Canada, followed by routes within Europe and Latin America. After these, China-Europe, Africa-Europe and China-Oceania pairs stand as very important MoM routes sources, with over 60 routes in the database each. These are followed by connections through the Asia-Pacific region such as Southeast Asia-Oceania, and between Asia and North America.

Figure 13.19 provides a visual representation of the main flows between regions. On the left side of the graph, the origins of the routes are represented, and on the right side, the destination, or sinks. Since the routes on the database are bidirectional, these connections can be also understood as the opposite way so, for example, the flow Europe-North America is the same as North America-Europe.

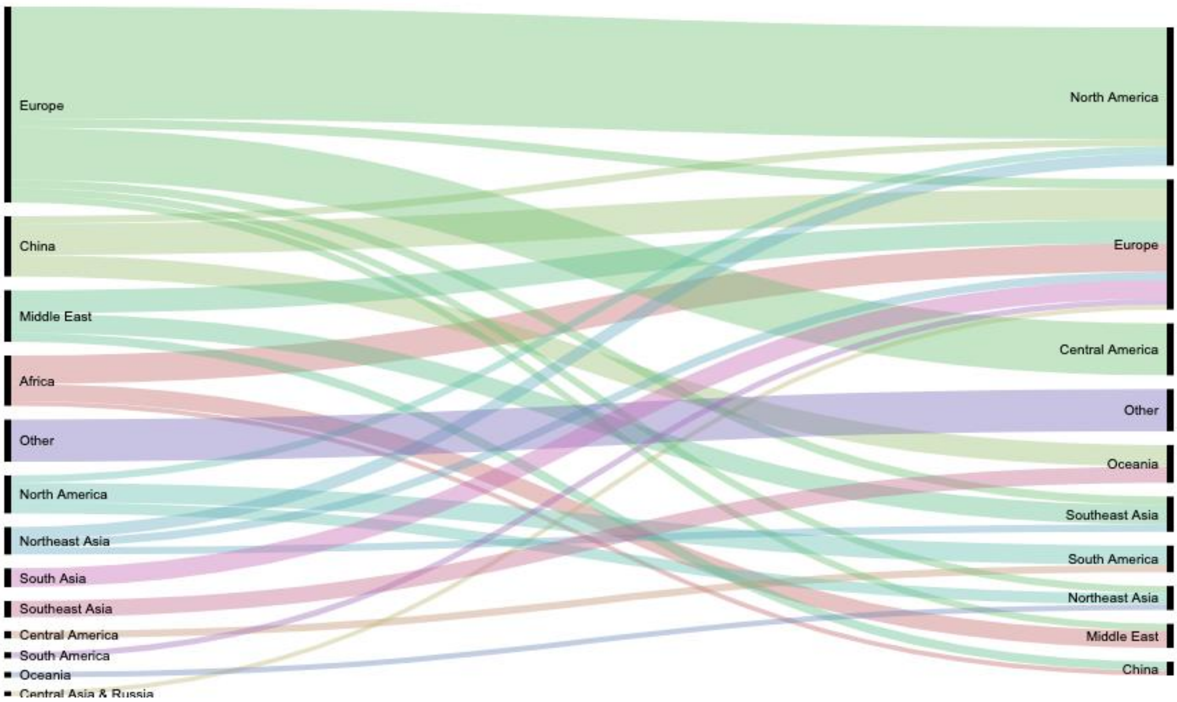


Figure 13.19. Middle of the Market main flows representation in 2018.

In Figure 13.20, a bar chart with the most important flows of the routes database is represented. As described, the main mid-haul connections are made between Europe and North/Central America with over a 30% of the volume of routes in total, followed by China and Europe with a 6% of the routes. The rest of the flows are very varied as shown in the chart and each of them represents less than 5% of the total number of routes.

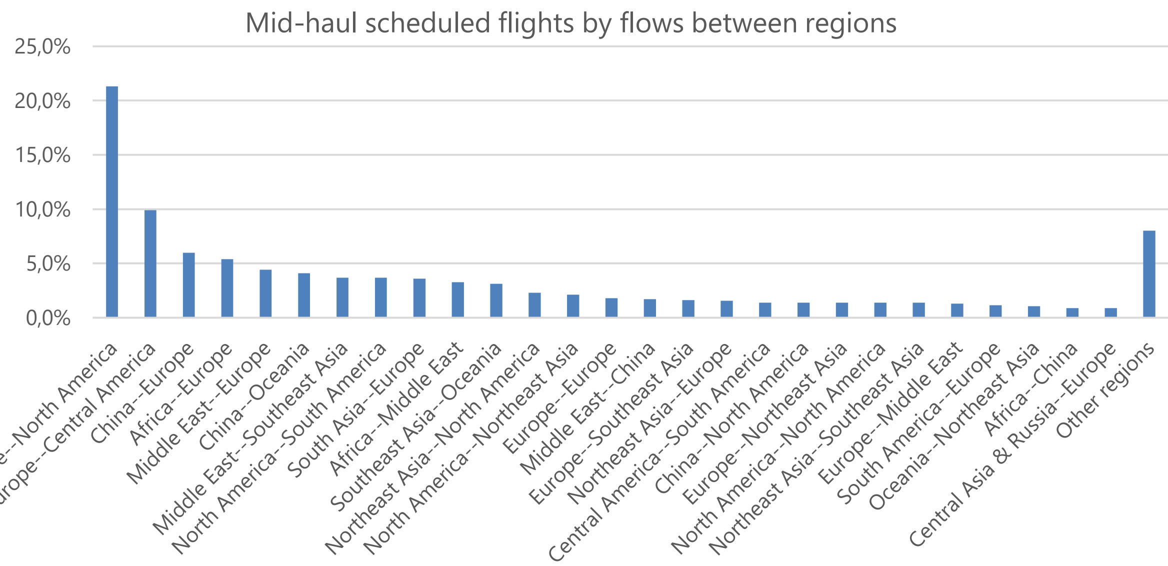


Figure 13.20. Mid-haul scheduled flights between regions

13.2.4.2 Analysis of used aircraft

In aircraft designing, a new model is built and optimized for a specific mission, that is, a specific flight distance. Nevertheless, operators have limitations on aircraft numbers and always try to have the maximum flexibility on the fleet. Apart from this, many other factors can affect the election of a specific aircraft model different from the optimum. In congested airports, for example, it is normal to use bigger aircraft such as wide body in order to maximize the number of passengers in every flight, since the cost of getting a slot is very high. This can happen as a basis, or seasonally depending on the region and the connection demand. Another example could be the crew training. Sometimes operators use wide-body aircraft in short-haul routes in order to provide specific training to the crew. This is why, normally aircraft fly routes which are, sometimes, out of their main goal.

There can be seen, for example, big jumbos such as the Boeing 747 flying domestic routes in Japan, as the infrastructure and demand require to transport a bigger number of passengers per flight. Or, another example is the use of mid-sized single aisles like the A320 or the 737 families in regional routes, where a regional jet such as the Bombardier CS100 or the Embraer 170 normally operate and are optimized for it.

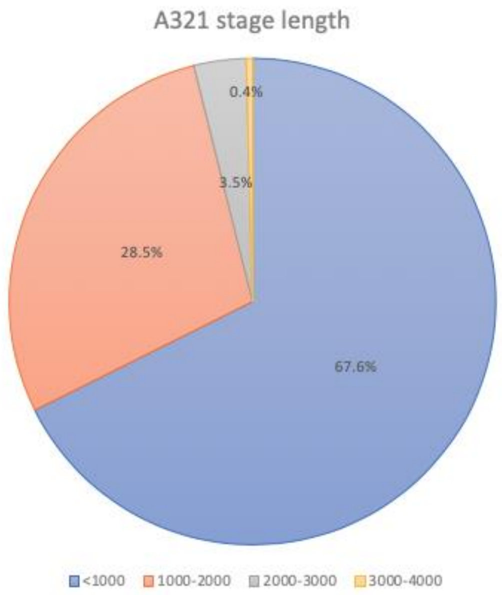
The *OpenFlights* database provides relevant information about the equipment (aircraft) used in every route, as well as the airline and the codeshare. In this section, an analysis of the MoM aircraft competitors and its average stage length will be done, in order to understand how air carriers, use every aircraft model and which the most common flown distance is.

Single-aisle average stage length

The most common passenger aircraft in the world is the Boeing 737 and the Airbus A320 families, formed by 3 different sized aircraft each. The typical range of these models rounds 3000-3500 nm and can carry from 120 to 200 passengers depending on the model. These features have made of these aircraft families a very versatile option for airlines since they can be used for multiple routes and markets with very competitive economics (low-cost per seat). For a more detailed description of these aircraft and their features see Annex 1, located at the end of the document.

The following figure shows the most sold A320 family models (A320 and A321, including both CEO and NEO[1] series) the number of routes by distance. It can be seen that both models are normally used for shorter flights, with a flight distance shorter than 1000 nm, these are domestic flights or flights within countries from the same continent. Flights of less than 1000 nm represent 74% of the A320 operations and 67.6% of the A321's. Flights between 1000 and 2000 nm represent 28.5% for the A321 and 24% for the A320. Longer flights, in the range of 2000-3000 nm are 3.5% of the total for the A321 and 2% for the A320. Additionally, the extended range of the A321 allows it to operate in routes of over 3000 nm, with 0.4% of the total. Regarding, the average distance flew, it is 820 nm for the A320, whereas for the A321 is a bit higher, 988 nm.

[1] CEO: Current Engine Option; NEO: New Engine Option



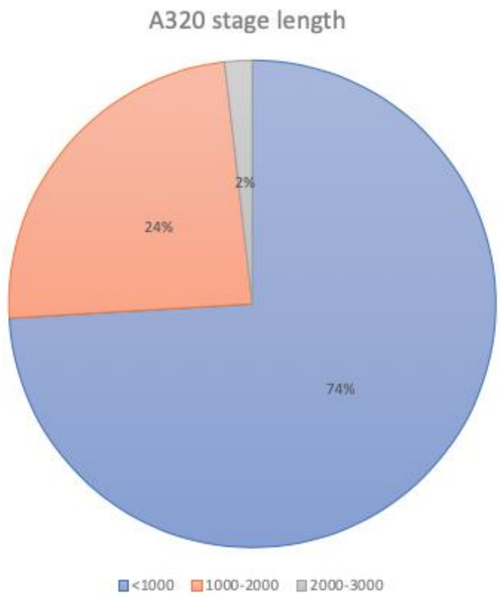


Figure 13.21. A320 and A321 routes by distance

The Boeing 737-800 has similar statistics than its Airbus competitors. In Figure 13.22, the percentage of each segment is represented, with a 71% for routes shorter than 1000 nm, 26% for routes between 1000-2000 nm and 2% for routes longer than 2000 nm up to 3000 nm.

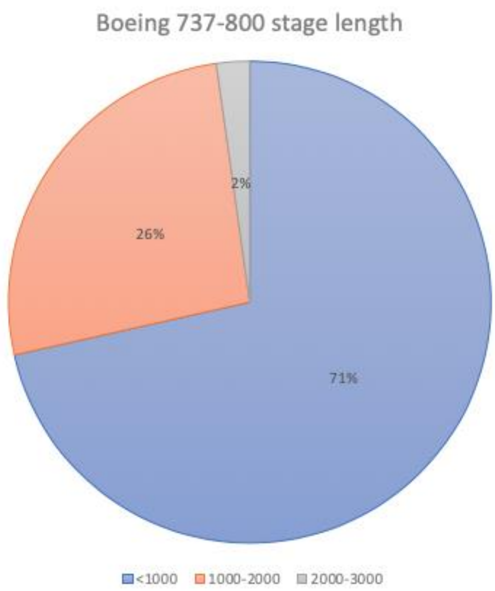


Figure 13.22. Boeing 737-800 routes by distance

Wide-body aircraft stage length

Most common wide-body aircraft that compete in the Middle of the Market is the 787-800 and -900, and the Airbus A330-200 and -300 which are expected to be replaced by the neo series -800 and -900 after 2019. Besides these, the new and bigger Airbus A350 competes also in this segment, covering the upper layer of the segment, mostly flying distances longer than 3500 nm. The routes database shows that the utilization of these aircraft is very varied, operating in both, short-haul and long-haul routes.

Figure 13.23 shows the Airbus A300-200 and -300 routes. According to the data, 28% of the routes are shorter than 1000 nm, which shows that the A330 models are widely used for regional and domestic flights. Nevertheless, more than a third of the total number of routes are considered mid-haul (from 2500 to 4500 nm), and around 23% of the routes belonging to the long-haul classification.

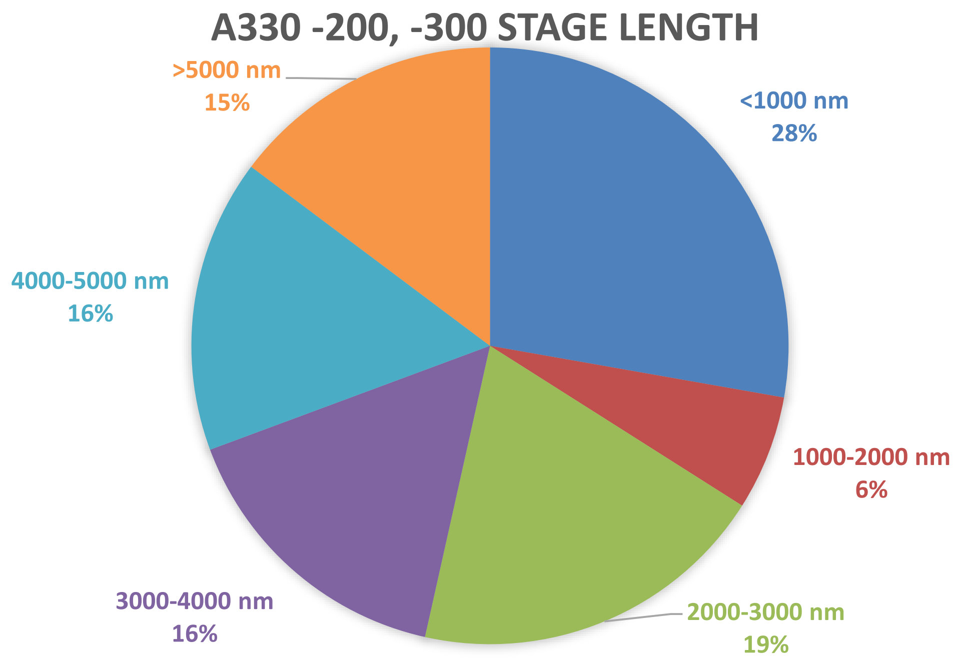


Figure 13.23. Airbus A330-200 and -300 stage length

The Boeing 787 Dreamliner is also a strong competitor in the Middle of the Market, with around 38% of its routes in the mid-haul segment, similar to the A330, in both the upper and the lower layer of the market by equal. Nevertheless, the 787 is mostly used for longer flights, since only 22% of its routes are shorter than 2000 nm. It is also a widely used ultra-long-haul aircraft, with around 20% of its routes being longer than 5000 nm. The following figure shows these statistics.

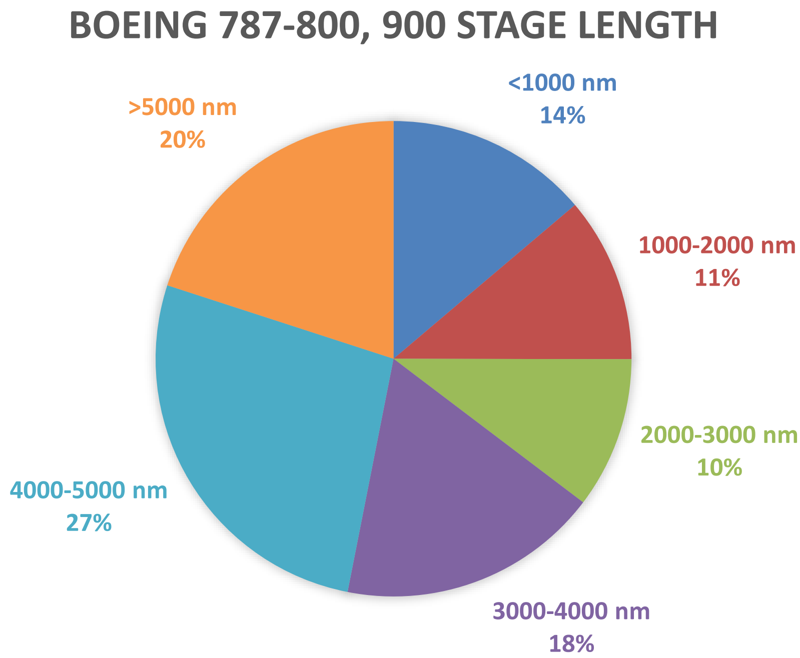


Figure 13.24. Boeing 787-800 and -900 stage length

The last analysed aircraft is the Airbus A350, which has been in service since 2015 and it is an aircraft which has been optimized for the long-haul segment. The graph presented in the following figure shows that the aircraft mostly operates in routes longer than 3000 nm, representing these flights 78% of the total. It can also be seen that the upper layer of the MoM (routes from 3500 to 4500 nm) represents 18% of the total routes, and the whole MoM around 43%. Besides, there is a small percentage of shorter routes, 7% for routes shorter than 1000 nm and 7% as well for routes between 1000 and 2000 nm.

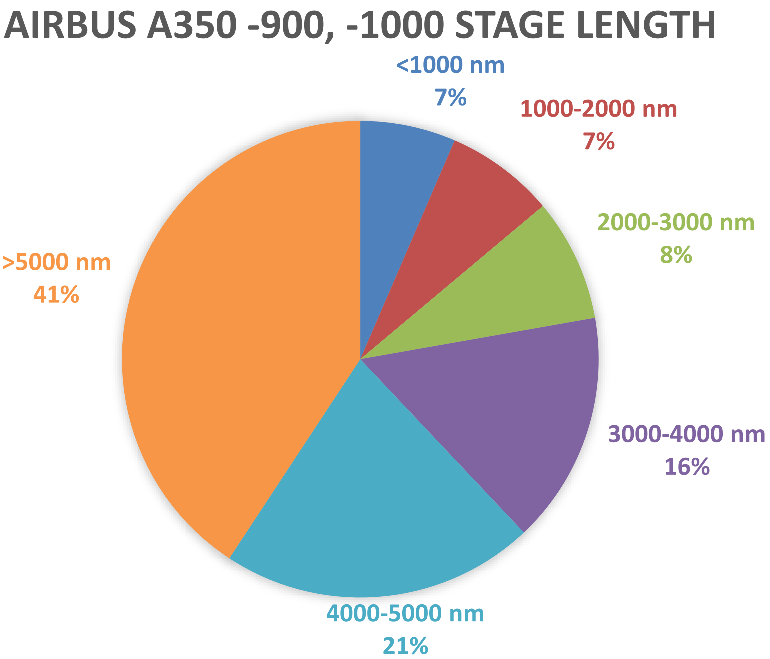


Figure 13.25. Airbus A350-900 and -1000 stage length

Boeing 757 and 767 stage length

The Boeing 757 and 767 models are the previous generations of the Middle of the Market models and they were introduced in 1983 and 1982 respectively, mainly because of airlines' necessity of smaller and more efficient airliners to cover transatlantic routes. The 757-200 was launched as a large single-aisle aircraft carrying up to 200 passengers and with 3900 nm of range. Two years later, a stretched version, the 757-300, with a capacity of 243 in a double class configuration was launched. The 767, on the other side, was designed as a wide-body, seven-abreast airplane able to carry from 190 to 340 people, and with a range from 3900 to 6400 nm, depending on the variant. The similar cockpit design of these models allowed pilots to get a single license and piloting both of them. For a more detailed description of these aircraft, see Annex 1.

From the 1049 B757 delivered, there are still 708 in service (May 2019), according to Norris and Flottau [26], around 15% of the fleet (106 aircraft) were parked and unused in 2015. The fleet of B767 in 2019 is formed by 807 active aircraft (May 2019) out of 1196 produced. The analysis of the *OpenFlights* routes dataset has provided the statistics shown hereafter.

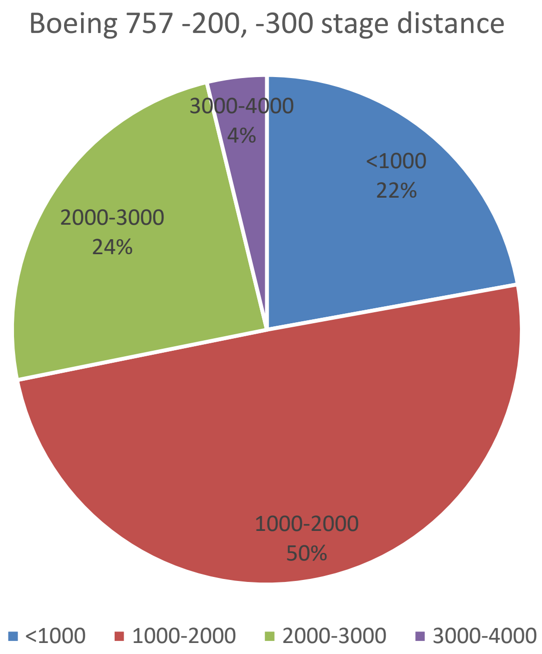


Figure 13.26. Boeing 757 stage length.

In the figure above, the distance distribution of the Boeing 757 routes is shown. Half of the routes are in the range 1000 – 2000 nm and about 16% of the total are mid-haul. The routes over the world's map are shown in the following figure.

Figure 13.27. Boeing 757 routes

From the statistics and the graph, it can be seen that this model is mainly used for longer domestic routes within the US since most of the operators are US-based airlines such as Delta or American Airlines. There is also a big number of routes of this airplane connecting Central Asia with Europe and the UK with the Canary Islands (all these routes are within the 2000-3000 nm range), as well as flights connecting China with Central Asia.

The distribution for the Boeing 767 is more focused on the mid-haul sector, with around 38% of the total number of routes in this segment. Nevertheless, the B767 is also widely used in short-haul domestic crowded routes shorter than 1000 nm, with about a 27% of the total, and longer domestic routes (18% of routes within 1000-2000 nm). The following figure compiles all this data.

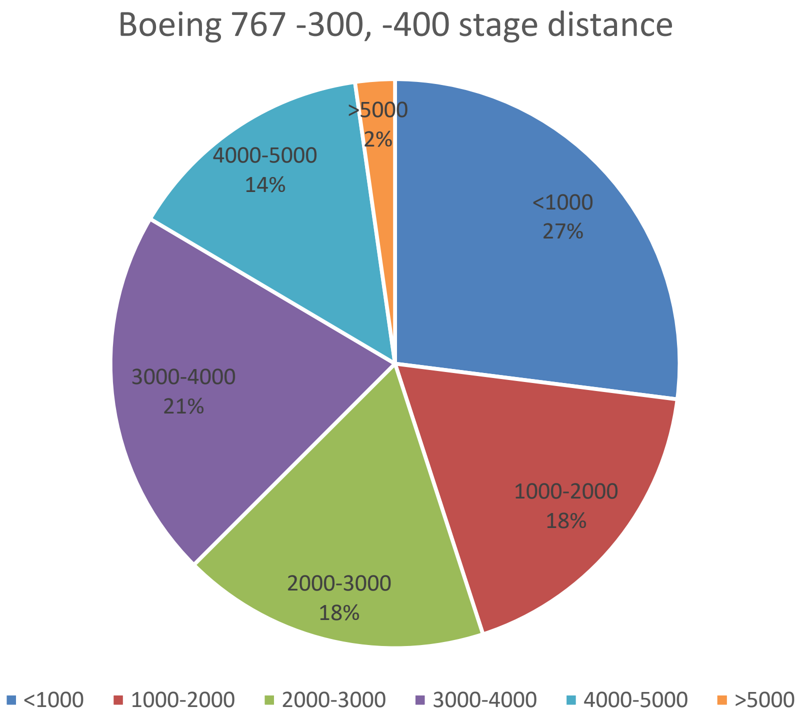


Figure 13.28. Boeing 767 stage length.

The routes over the world's map are shown in Figure 13.29. It can be seen that there's a big utilization of this model over transatlantic routes, and it represents its main operation frame. Additionally, there are many flights connecting the West and the East of the US and flights between South America and Europe.

Figure 13.29. Boeing 767 routes

Finally, a comparison of the two models is presented in Figure 13.30, compiling the statistics previously shown in Figure 13.27 and Figure 13.29. As stated in the graph, the Boeing 767 has a small number of routes more than the Boeing 757, and regarding the Middle of the Market, it dominates against the single-aisle models. The 38% of the B767 routes correspond to the mid-haul against 16% of the B757.

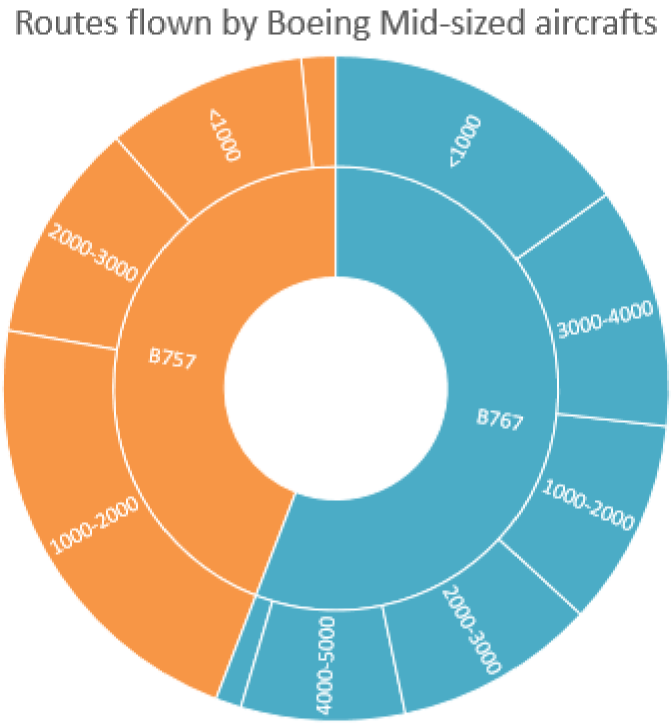


Figure 13.30. Boeing 767 and 757 operations comparison.

13.2.4.3 MoM market share

The purpose of this section is providing a general overview of the Middle of the Market sector, by assessing the aircraft that operate in this segment. Figure 13.31 shows the market share of medium-haul routes by aircraft model. This figure has been obtained through the routes data analysis performed in the previous sections and it has allowed to determining exactly the aircraft that are currently operating within the MoM market and, specifically, for medium-haul routes, which is the target range considered for the study.

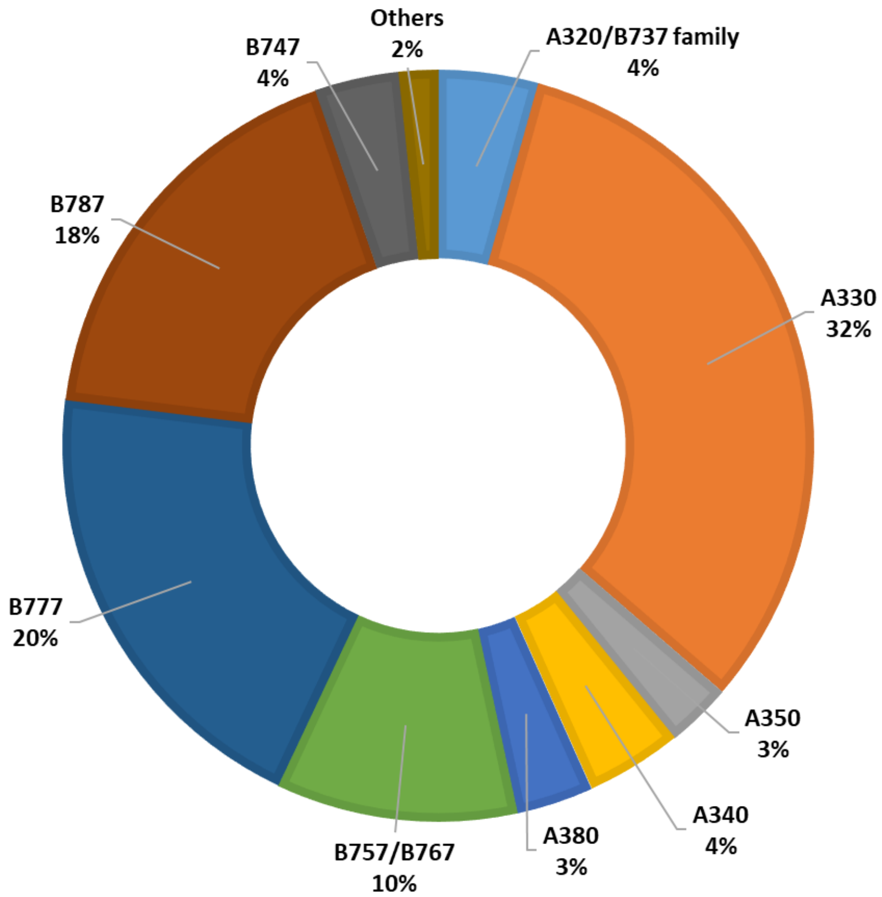


Figure 13.31: Market share in medium-haul routes

Several relevant aspects can be extracted from Figure 13.31. First, it shows that almost all aircraft with market share for the MoM segment belongs to Airbus and Boeing models. Only 2% of the total MoM market share belongs to other manufacturers, which clearly demonstrates that both companies dominate this market.

The A320 and B737 families, which represent the single-aisle segment, absorb together 4% of the market share. It is a small proportion, but it is necessary to take into account that, according to the data, some models used for these routes are previous versions such as the B737 Next Generation and A320ceo families, whose range is lower compared to the most modern versions. It is very likely that this percentage will increase when the new variants such as the A321neoLR and B737 MAX 8 remain several years in the market and fly a higher number of routes.

On the other hand, the figure shows that wide-body aircraft such as the A330, B787, B777 possess a significant market share, reaching between the three families a market share of 70%. This value indicates that the MoM market is dominated by these aircraft, which is an interesting data taking into account that their range is quite higher than the target range chosen. According to the routes data, several models used for these routes are old versions which have been in the market for a long time. This is the case of the A330, which absorbs 32% of the market share, belonging this value to the A330-200/300 variants. With the introduction of the new versions, the A330neo, it is expected that this scenario will change in the future as these models are retired from the market.

With the B777 occurs a similar situation. The 20% of the market share belongs to the variants B777-200/200ER and B777-300/300ER, old models whose replacement is expected with the new variant known as B777X, which is planned to enter in service around 2020. The B787 is a more recent aircraft with still several years of operational life. Therefore, it is expected that this percentage will remain in the following years, although it is very likely that the new models will absorb part of it.

Other aircraft even larger, such as the A350, A340, B747 or A380 are also used for these routes, although in a much smaller proportion. It is expected that their market share will be absorbed by the A350, a more recent aircraft with similar range and capacity capabilities and less fuel consumption.

Finally, the B757/B767 fleet represents 10% of the market share. However, these models are no longer in production and they are expected to be retired in the upcoming years. The main objective of the new Boeing airplane is to replace this fleet and to absorb part of its market.

Therefore, several of the models, which are currently operating in the MoM segment, will be, replaced in the next years, as demonstrated in Figure 13.32. This figure shows the backlog of these aircraft, indicating that old models such as the A330-200/300 and the B777-200/300 do not have hardly backlog and new orders belong to their new versions, the A330neo and B777X. It also shows that models like the B737 MAX 8 and A321LR, which have just entered the market, are very successful programs with more than 2000 aircraft of the backlog. For this reason, it is very likely that these models will absorb part of the market share of the Middle of the Market, although they are designed for the single-aisle segment.

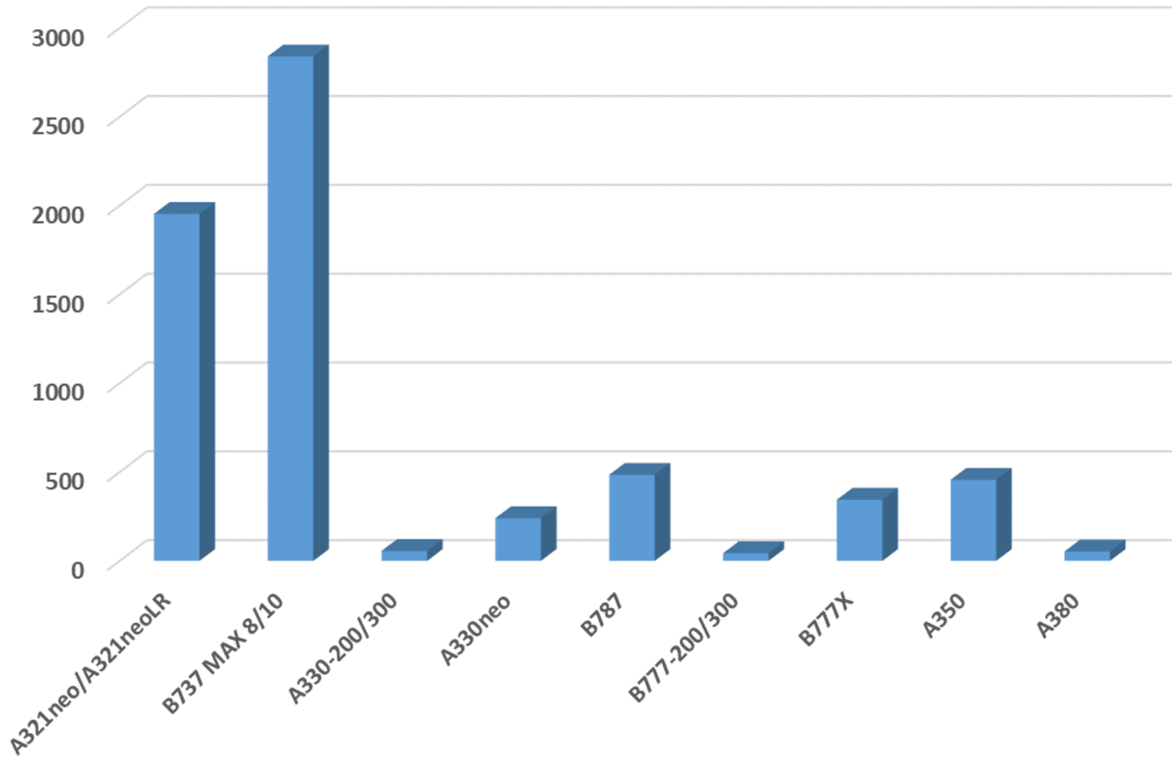


Figure 13.32. MoM aircraft backlog (data as of December 2018)

13.2.5 Air transport market forecast

Forecasting the number of airplanes demanded by airlines and passengers in the future is a complex problem affected by important uncertainties. Although a number of approaches and methodologies have been developed by the academia and the industry, the accuracy of any fleet demand forecast relays very much on a deep knowledge of the industry and on reliable data about the evolution of the various markets and segments. The general process and methodology for developing such prognosis studies are detailed in the Annexes.

A selected group of companies, including manufacturers, consultancies and governmental agencies, produce regular updates of short, medium and long-term forecast that are considered a reference for any market study in aviation. The aim of this study is not to build an additional forecast, but to integrate the best publicly available long-term forecasts, as well as hypotheses and trends highlighted by reference reports about credible expected evolution of airplane fleets demand, production, retirement and delivery. All these inputs about the expected long-term evolution of the global world fleet market will be used to dimension the possible size of the Middle of the Market fleet demand that concerns this study. In that way, the current study will benefit from the best knowledge in the market and will integrate the most optimist and also conservative approaches and hypotheses about the global commercial aircraft market. This will allow us to estimate a range of values for the expected long-term passengers and fleet demand in the Middle of the Market segment.

In this chapter, we manage five worldwide studies covering a forecast period of 20 years and global passenger fleet:

i) Boeing Commercial Market Outlook 2018-2037 Co;
ii) Airbus Global Market Forecast 2018-2037;
iii) JADC Worldwide Market Forecast 2018-2017,
iv) United Aircraft Corporation (UAC) Market Outlook 2017-2036, and
v) The Airline Monitor Commercial Aircraft Market Forecast 2017 – 2040.

Boeing and Airbus both release each year a twenty-five-year market forecast for aircraft demand which provides some insight into the qualitative nature of the market demand and how the two major producers expect demand to evolve over the coming two decades. As it has been discussed in Section 13.2.2, each of the manufacturers makes their own segmentation of the market, with blurred boundaries between types of planes.

The JADC (Japan Aircraft Development Corporation) continuously collect and analyse data relating to the world commercial aircraft market, being its "Worldwide Market Forecast" the long term forecast for air passenger and air cargo demand, as well as airplanes, demand for turboprops, passenger jets, jet freighters and aero engines over the 20-year period covering 2018-to 2037.

The UAC issue of Market Outlook 2017–2036 reflects the vision of United Aircraft Corporation, in modern Russia, on the air transportation development prospects and the formation of demand for new commercial aircraft, and it considers significant market factors in the modernization of Russia's aviation infrastructure.

The Airline Monitor is a leading source of data and forecasts for world's airlines and commercial aircraft, which are published six times a year, bi-monthly from February to December, and they are available in both printed and electronic form.

All previous prospects are analysed hereafter and complemented with information about forecast from other reliable sources including the own project knowledge and projections.

Although the overall methodology in all these studies is similar, the main differences among them will be highlighted, and alternative hypotheses and differences in values will be used to build up a set of scenarios, including reference and extreme (optimist and pessimist) value forecast. We do not pretend to qualify one forecast against others but to use them all to predict the most acceptable range of values.

13.2.5.1 Airbus Global Market Forecast 2018-2037

Every year, Airbus [27] delivers its market prospects for the following 25 years. In this market forecast, the company estimates the evolution of air traffic over the next years using an econometric model based on the GDP growth, wealth and middle-class share growth estimations.

The main driver for the air transport demand is the wealth effect, that is if people own more money their predisposition to travel will increase, and so it will do the air transport demand. The evolution of the middle classes is an excellent proxy for this relationship. In 2002, about a quarter of the world's population could be described as "middle class", today it is considered to be around 40% and by 2037, Airbus forecasts it to be around 57%.

Business models are an important part of the evolution of air transport. Airlines evolve over time to meet the requirements of the passengers to take advantage of the opportunity and to respond to the competition. The low-cost model has helped to deliver additional growth, through the provision of low fares and new city pairs largely. In recent years, the low-cost model has evolved including ultra-low-cost modalities as well as starting offering seats in the long-haul segment. This fact has made air transport more accessible to the middle class.

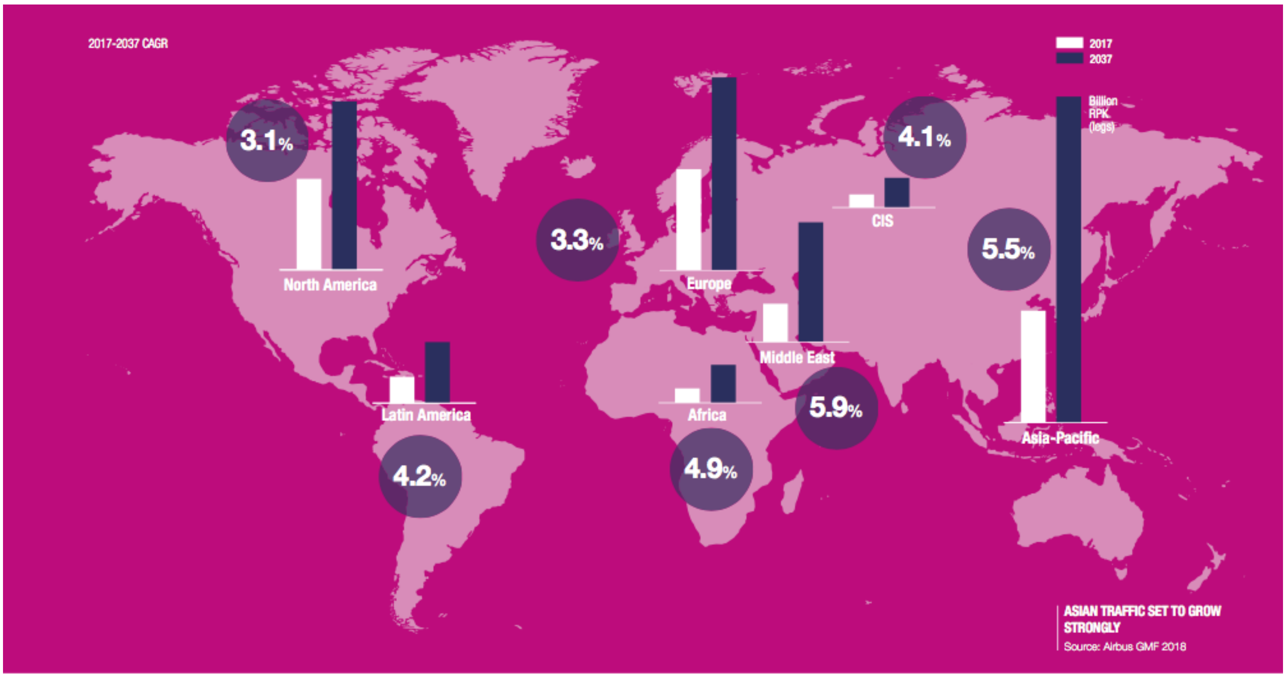


Figure 13.33. Airbus' air traffic growth forecast. Source: Airbus GMF 2018. [27]

The figure above shows the estimations of air traffic growth in the following 20 years made by Airbus. It can be seen that Asia-Pacific, Middle East and Africa will be the regions with the biggest growth percentage by average. Traffic from these emerging countries will rise at a rate of 6.2% per year according to Airbus' report. Passengers travelling between emerging countries is forecast to grow at 6.2% per annum and will represent a growing share of air traffic, from 29% of world traffic in 2017 up to 40% by 2037. China will also experiment a big growth, especially in domestic traffic. According to Airbus, Chinese domestic traffic will multiply by a factor of 3.5 over the next 20 years. Indian subcontinent and domestic flights inside India will carry 5.9 times more passengers than in 2017. It is also remarkable from this report that India will experiment with the fastest growth at a rate of 5.4% per year.

According to fleet forecast, Airbus remarks the increase of the single-aisle fleet, which has evolved much faster than the wide-body fleet over the last ten years. This is due to a higher number of seats in this family of planes and longer-range capabilities that opened new routes. The average distance flown by single-aisle aircraft was 422 nm with 140 seats on average back in 1999 and 586 nm with 169 seats on average. Airbus forecasts 36,563 new deliveries on the following 20 years, composing a global fleet of 45,265 aircraft, comparing to the 2018 global fleet of around 19,000 aircraft. This refers to 100+ seats aircraft and does not include Russian models.

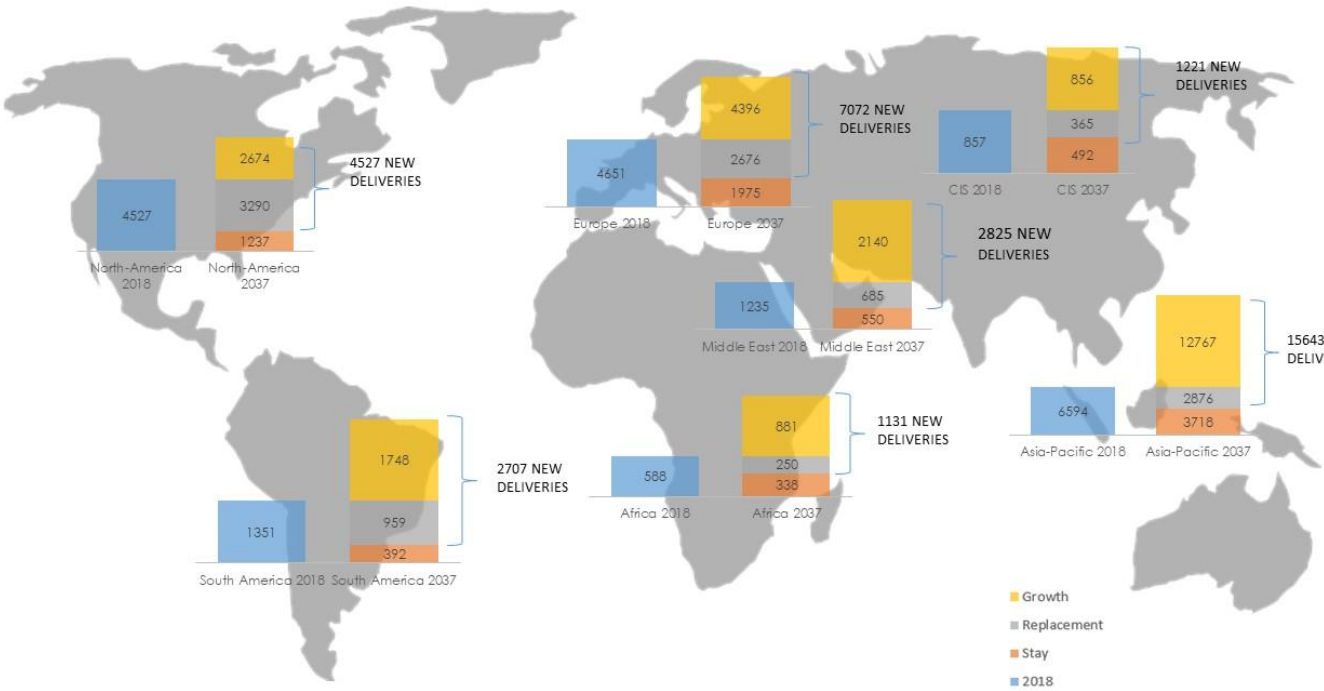


Figure 13.34. World fleet evolution 2017-2037 according to Airbus GMF 2017-2037.

The figure above shows the fleet evolution regionally over the next twenty years. It is clearly seen that Airbus forecasts the Asia-Pacific countries as the main drivers of the aerospace sector, with more than 15,643 deliveries representing a growth of almost two times the actual fleet, and around the 40% of the world fleet. The Middle East will multiply its fleet by a factor of 2,7 and other developing regions such as South America, Africa or the Commonwealth of Independent States will duplicate its air fleet. On the other hand, North America, the region that had boosted air transport on its early beginnings will no longer dominate the market, and its fleet growing perspectives are around 50% of the current fleet, according to this Airbus report.

According to Airbus, small aircraft such as the Airbus A320 or the Boeing 737 will dominate the market, representing 76% of the deliveries worldwide, and 54% of the value.

13.2.5.2 Boeing Market outlook 2018-2037

Like its European competitor, Boeing also delivers its own market forecasts yearly. In this commercial aviation outlook, the US manufacturer points out the three macro-environment dimensions that drive airplane demand.[28]

- On the one hand, there is the underlying demand for air travel, which is lead fundamentally by economic and income growth. The growth of the world GDP is mainly composed of the changes in the large emerging countries like China or India. This growth causes bigger support for air travel due to higher consumer spending. Economies like China are transitioning to a more service-based economy due to higher automation relative to manufacturing worldwide, which will support air travel in the future. The higher incomes will lead to more predisposition to travel, as tourism becomes a growing part of consumer spending. Tourism worldwide is expected to grow at a rate of 4% yearly over the next 10 years. Apart from the intrinsic consequences of a bigger economy with higher spends, airline business models will play an important role in air travel demand. Low fares business models, such as the ultra-low-cost carriers will expand the number of passengers as the accessibility to air travel eases.

- Air travel demand is followed by the regulatory, infrastructure and technology environment. The increasingly liberalized markets have been an important asset to the commercial airline industry. Open Skies recent agreements have promoted strong competence between air carriers and encouraged more traffic by removing constraints to air transport. The expectations are that this trend will continue and bring lower prices for air travel. Another key driver for the future demand will be the airport infrastructure and congestion. In recent years, airports have experienced problems with operational capacity due to high passenger growth. Operational efficiency of airports and airlines is a main priority over the last few years, and Boeing expects this dynamic to continue and challenge air travel demand.

- Besides, economy and infrastructure, the products and strategies followed by the airlines are also the main drivers of the sector. Low fares boost demand with strategies like fleet standardization (single aisle), lower yield and higher load factor, ancillary revenues… etc. New trends like ULCCs (ultra-low-cost carriers) are expected to arise in the future, and also the entry of LCC into long-haul routes. Network airlines such as IAG will also be important in the future, with products spanning in the low-cost, long-haul sector, like LEVEL.

With these three environments identified as the main boosters of the demand, Boeing forecasts a 4,7% average annual passenger traffic growth in the next 20 years. Asia-Pacific region will be the one contributing the most to passenger growth, with an average rate of 5,7%. An insight made by Boeing into this region shows that China is on its way to becoming one of the world's largest aviation markets, accounting nearly 20% percent of the global traffic by 2037, followed by Southern-Asian developing countries such as India, that will quadruple its fleet. Africa, on the other hand, is the region with the highest growth rate of the world, with 6% per annum by average. The US company forecasts African connectivity will be improved over the next 20 years resulting in a great increase in the transport. Nevertheless, it will continue being the region with the least developed aviation sector. The following map shows the growth rate of every region listed by Boeing in its Commercial Market Outlook.

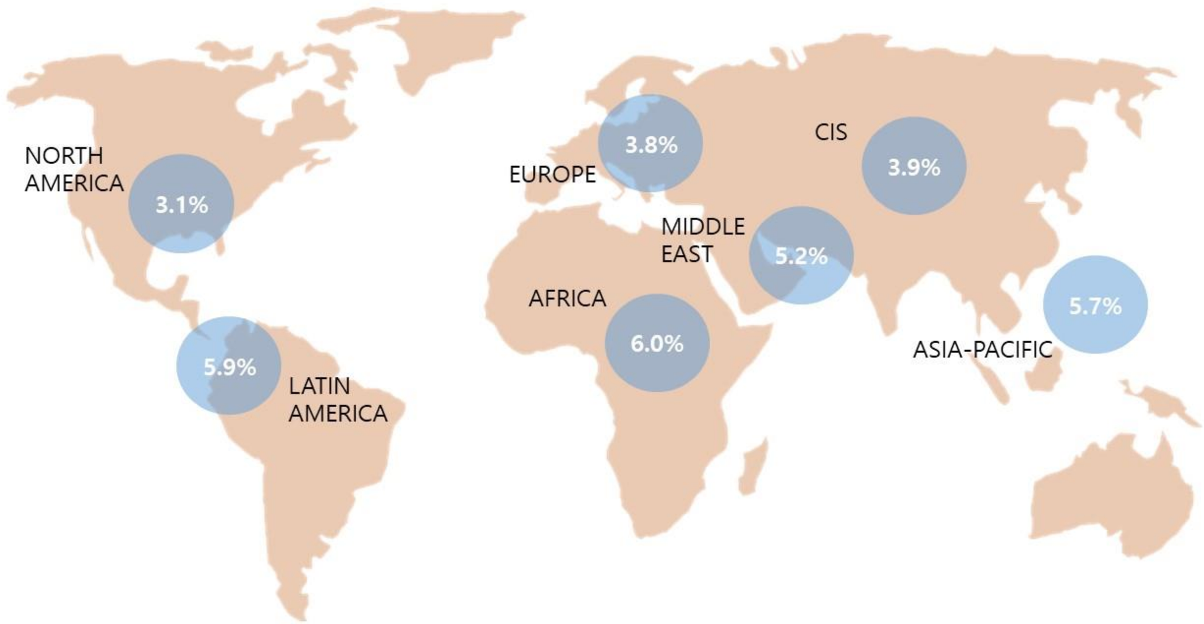
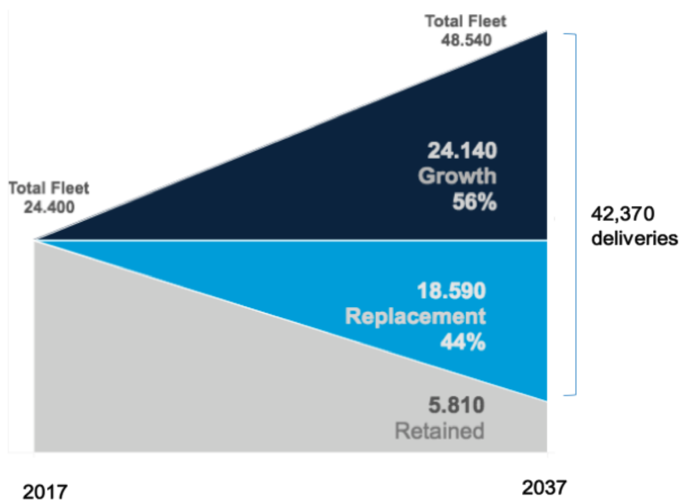


Figure 13.35. Boeing's traffic growth forecast by region

Unlike Airbus, Boeing considers a wider range of aircraft for its Commercial Market Outlook. The US company also considers the regional jet fleet, which sums up a global fleet of 24,000 at the beginning of 2018, a bigger size than the 21,000 aircraft considered by Airbus in its forecast. Boeing forecasts the global fleet to double to nearly 48,000 by 2037, with more than 42,700 new deliveries. Most of these deliveries will account to single-aisle aircraft, alongside more than 9,000 new wide-body aircraft. Asia-Pacific region will receive more than 40% of these new aircraft, as well as an additional 40% to be delivered to Europe and North America. The remaining 20% will satisfy the demand of Russia and Central Asia Regions, Middle East, Latin America and Africa.

By 2017, Boeing's data shows that single-aisle airplanes composed 69% of the global fleet, whereas in 2037 it will account for around 74%. Boeing states that the long-haul market will be dominated by smaller wide-body airplanes due to the clients' preferences. The irruption of the single-aisle aircraft into transatlantic routes will also make a turn into the market since the aircraft average size will become significantly smaller.



The following figure shows the global fleet by end 2017 and the forecast of the distribution of the fleet around different regions of the world in 2037. Developing regions such as Asia-Pacific, Latin America, Middle East and Africa will more than double their current fleet, whereas, for

Europe and North America, the number of aircraft will increase at a lower rate.

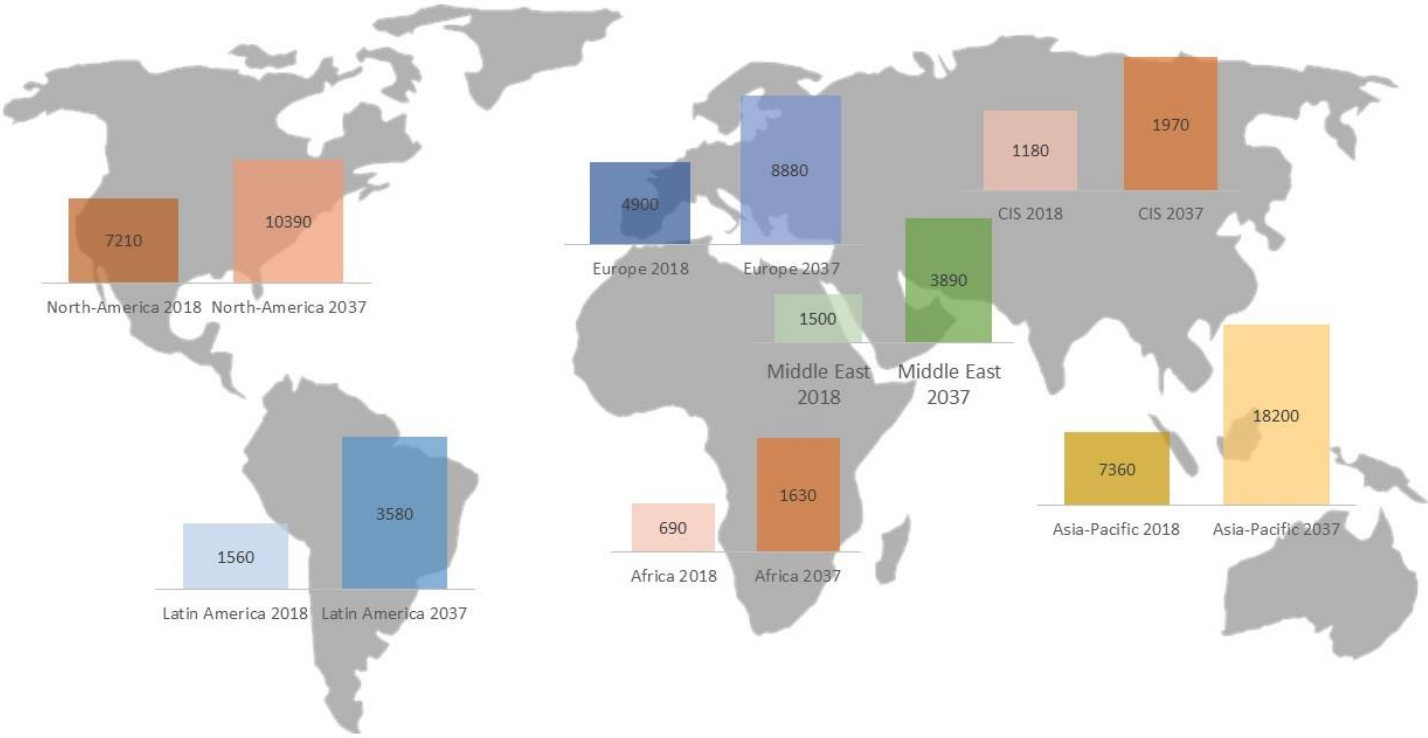


Figure 13.36. Boeing's global fleet forecasts.

13.2.5.3 JADC Worldwide Market Forecast 2018-2017

Japan Aircraft Development Corporation is a consortium of Japanese Aircraft Industries for the development of commercial airplanes through studies, research and other appropriate means so that it will promote a competitive Japanese aircraft industry. Every year, the consortium releases a worldwide forecast of commercial aviation, in order to identify future trends and possible gaps in the market for the Japanese industry.

On its latest version (2018-2037), JADC makes a forecast of air transport passengers and aircraft fleet and deliveries over the next 20 years. The Japanese consortium identifies several aspects that will be directly influential for the demand for air transport and, consequently aircraft production. Those market drivers are described hereafter. [29]

- **World Economy**, quantified by the GDP growth trends, is the main driver of air transport according to JADC. The global GDP is forecast to grow at 2.9% per annum by average from 2018 to 2037, with emerging economies like India, China or the Middle East leading this growth. The Asia-Pacific region will account around 40% of the global GDP by 2037, half of it belonging to the Chinese economy.
- **Crude Oil Prices.** Changing oil prices have a direct impact on airline profits. From 2014 airlines have benefited from relatively low oil prices. The rapid development of emerging countries

occasioned in the past a very high rise on the oil prices, and it was countered around 2014 with the opening of new supply points in North America, Brazil, Russia and West Africa. The forecasts on crude oil prices account for a drop in the short term due to oversupply and the economic standstill. In the long term, it is expected that the oversupply will be resolved due to the rising demand for energy accompanying economic development in emerging countries and that crude oil prices will rise again, although the proliferation of energy saving technology, as well as the transition to alternative energy sources, will reduce demand for crude oil.

- **World Population.** Middle-class income has been growing rapidly, especially in emerging countries like those in Asia. The population with annual incomes between $5,000 and $35,000 will rise from 2.1 billion in 2010 to 3.1 billion in 2020. According to population estimations, the United Nations forecasts the global population to be over 9 billion people in 2037 up from 7.55 billion in 2017. The number of urban habitants will increase by 7% in 2037 lead by emerging countries.
- **Demand for Travel.** International tourism is one of the main drivers of the air travel demand since over 50% of the international tourists move by air. In 2016, the number of international tourists reached 1.2 billion and future forecasts point to be 1.8 billion by 2030.

The Japanese consortium forecasts a growth rate of 4.5% yearly from 2017 to 2037, and RPKs will multiply by a factor of 2.4, reaching 18.6 trillion. For the forecast period, it is predicted that the real yield will fall 0.6% per year due to the increment of competition between airlines.

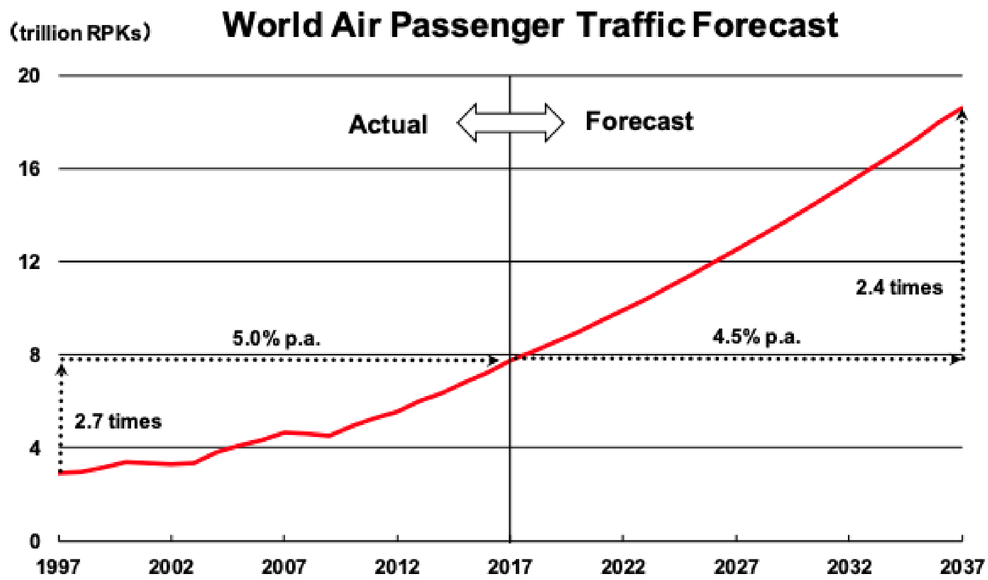


Figure 13.37. World Air Traffic forecast. Source: JADC

JADC forecasts point Asia-Pacific region as the one with the highest rate of growth in terms of RPKs over the next 20 years. This region will represent 38% of the total traffic worldwide, up from 32% nowadays. Developed regions such as Europe and North America will lose their leadership in terms of RPKs from 47% of the total traffic in 2017 to 40% in 2037. This is due to the rapid development of regions such as Asia, the Middle East or Latin America.

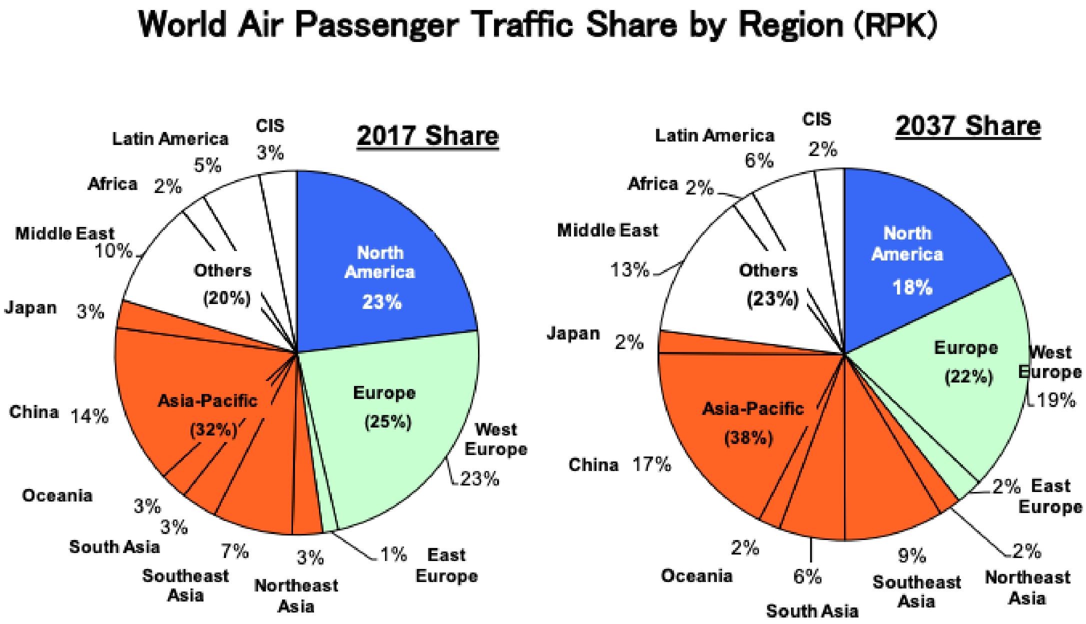


Figure 13.38. Traffic share by region. Source: JADC

Regarding aircraft forecast, JADC made its estimations based on a total fleet of 22,337 jet airplanes in 2017, which includes regional, narrow-body and wide-body western and Japanese-built jets. As commented above, JADC forecasts a 4.5% growth per year of the world air traffic. Although its downward trend, the world fleet will increase 1.78 times to satisfy the necessary ASK, reaching 39,867 airplanes in 2037. There will be some factors suppressing the increase of required airplanes, including rising load factors, more seats available per aircraft, and an extension of the annual flight hours due to the improved maintenance. Among these, 16,000 airplanes will replace current airplanes, accounting for 48% of total new deliveries. The remaining 17,530 airplanes will be due to new demand in response to growing air passenger demand.

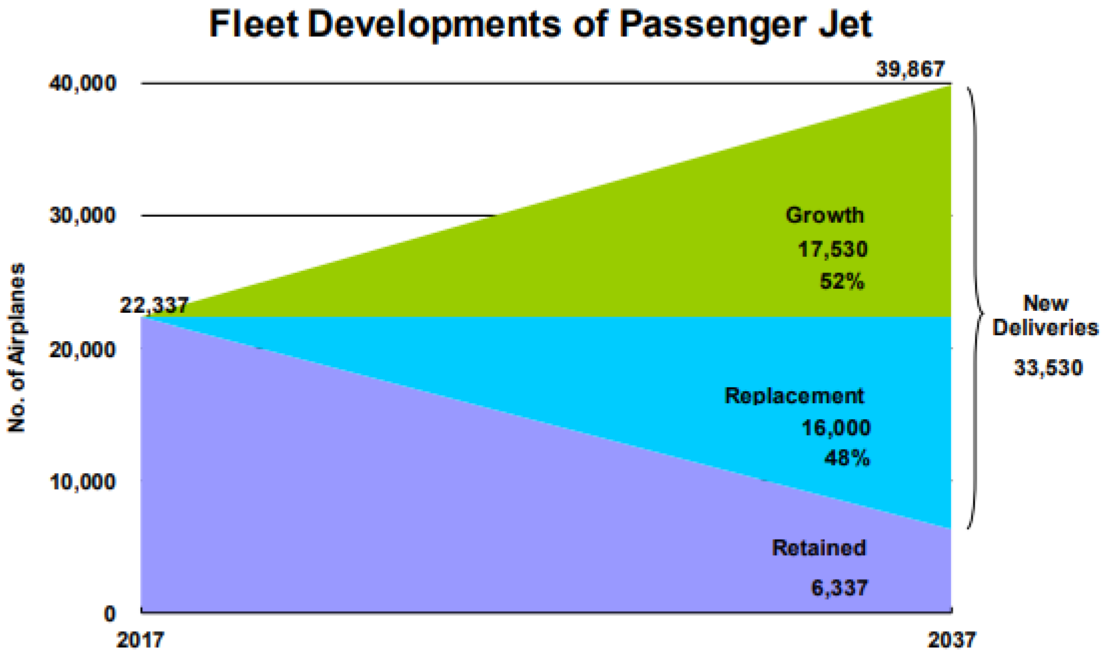


Figure 13.39. Aircraft world fleet 2037. Source: JADC

The JADC makes special emphasis on regional jet production due to the importance for Japan aircraft industry of the MRJ90. After the 11S attacks, the increment on the CASK due to the high oil prices headed airlines to hastily replace the regional jets with fewer than 50 seats to bigger size models like the CRJ900, ERJ175 or the MRJ900, with around 90 seats mono class that can be reduced up to 76 seats with the introduction of a first-class. This type of jets will account the majority of regional jets by 2037, of a total fleet of 3,410 airplanes. By that time, the share of regional jets of the total fleet will be reduced due to the replacement of some of them with single-aisle aircraft.

Single-aisle fleet will increase their share of the world fleet, representing 65% of the deliveries in the 2018-2037 period. Larger narrow-body airplanes are being used rather than smaller versions such as the A319/B737-700, from the point of view of soaring fuel prices and airport congestion, which leads airlines to increase the number of seats available per flight. JADC believes that the demand for bigger planes that can fly longer is likely to increase in the future, which includes big narrow-body airplanes with better cost-performance. Nevertheless, these airplanes seem to be reaching their limits regarding seat capacity, which could lead to their replacement by wide-body jets. Nonetheless, regarding airplane numbers, the narrow-body types will still account the majority of the demand.

The number of wide-body jets with 230 or more seats will increase from 4,252 at the end of 2017 to 9,989 in 2037, with the share increasing from 19.0% to 25.1%. 3,191 jets will be retired, and 8,928 new jets will be delivered to airlines between 2018 and 2037. The share of new deliveries will be 26.6%. The following figure shows the share of the fleet and new deliveries for the three types of aircraft discussed.

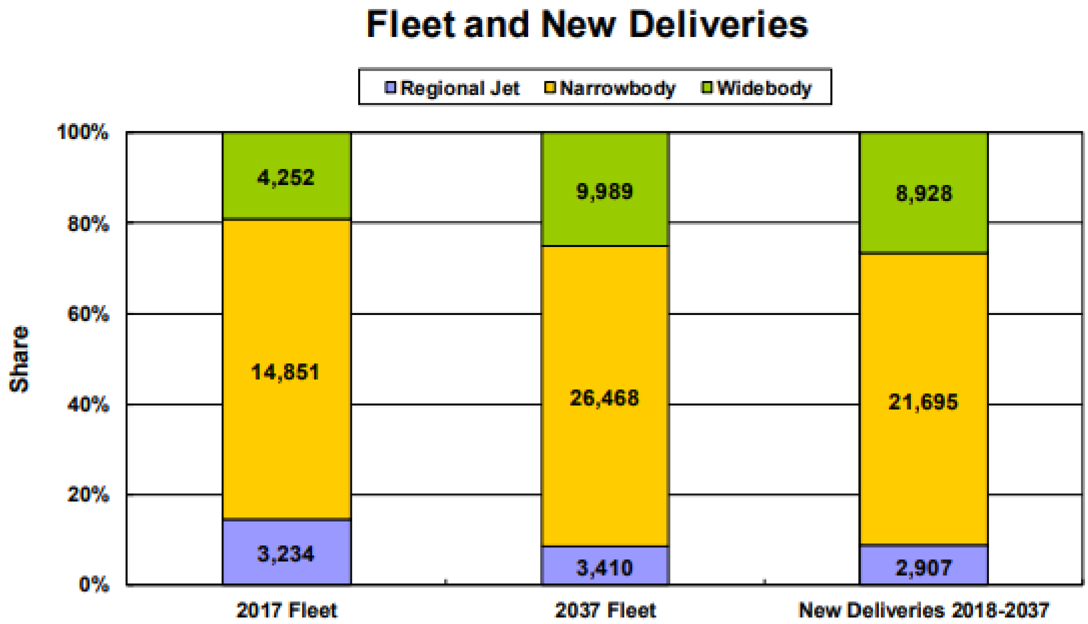


Figure 13.40. Fleet and new deliveries share 2017-2037. Source: JADC

13.2.5.4 United Aircraft Corporation (UAC) Market Outlook 2017-2036

United Aircraft Corporation is a consortium created by the Russian government with the aim of strengthening and unite the Russian aerospace companies in order to consolidate the aircraft industry in the country. In 2017, the corporation released a market outlook for the period 2017-2036. The significant aspects of this release are discussed hereafter. [30]

UAC remarks on the growth of emerging regions like Asia-Pacific and the structural changes in the market due to the loss of leadership in traffic volume share of Europe and North America. During the forecast period, China will demonstrate the highest dynamics of the passenger air transportation market. UAC forecasts the Chinese volume will equal the European one by 2036. In terms of passenger turnover growth, the Middle East and Latin America are likely to be significantly ahead of North America and Europe; however, a relatively small population (referring to the Middle East) and much more modest aggregated GDP will help the regional leaders to keep a significant distance.

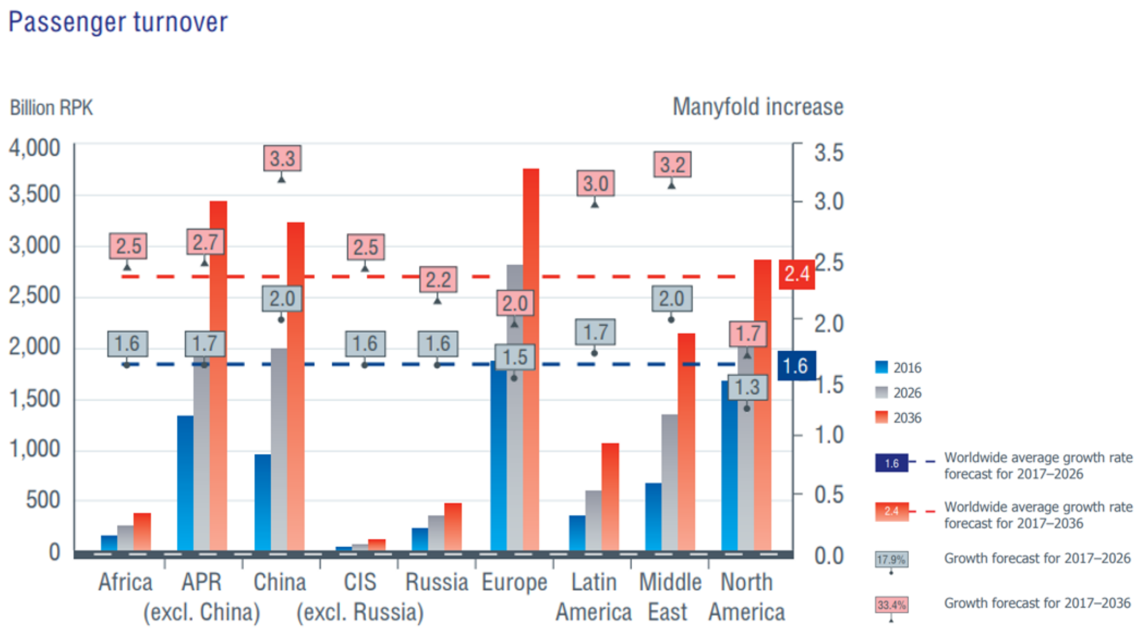


Figure 13.41. UAC's passenger air traffic forecast. [30]

The graph above shows the passenger traffic evolution in terms of RPK in different regions of the world. The data presented by UAC places China as the fastest-growing region in the world, reaching more than 3,000 billion RPK by 2036. Nonetheless, according to UAC, Europe will prevail by being the region with more traffic in the world, followed by the Asia-Pacific region (excluding China), that will reach nearly 3,500 RPK in 2036. Regions like Latin America and the Middle East will also account high growth rates, especially during the 2017-2026 period.

UAC also analyses fleet evolution over the period 2017-2036 in the different regions of the world. The graph below shows a summary of the information included in this report, with data about fleet divided into three different segments: turboprops and regional jets, narrow-body aircraft and wide-body aircraft. The first graph shows the fleet by end 2016 and the second the forecast demand for the period 2017-2036.

Figure 13.42 shows the market forecast made by UAC for the period 2016-2036. On it, it can be seen that narrow-body airplanes will continue leading the market, especially in Europe and North America, with more than 6,800 deliveries in each region, according to UAC forecasts. Regarding the wide-body market, Middle East is the only region where this market overtakes the narrow-body due to the larger distances travelled by air transport consumers. Fast-growing China will receive over the forecast period more than 6,150 single-aisle airplanes, stating very high growing perspectives compared with its 2,500 current fleet.

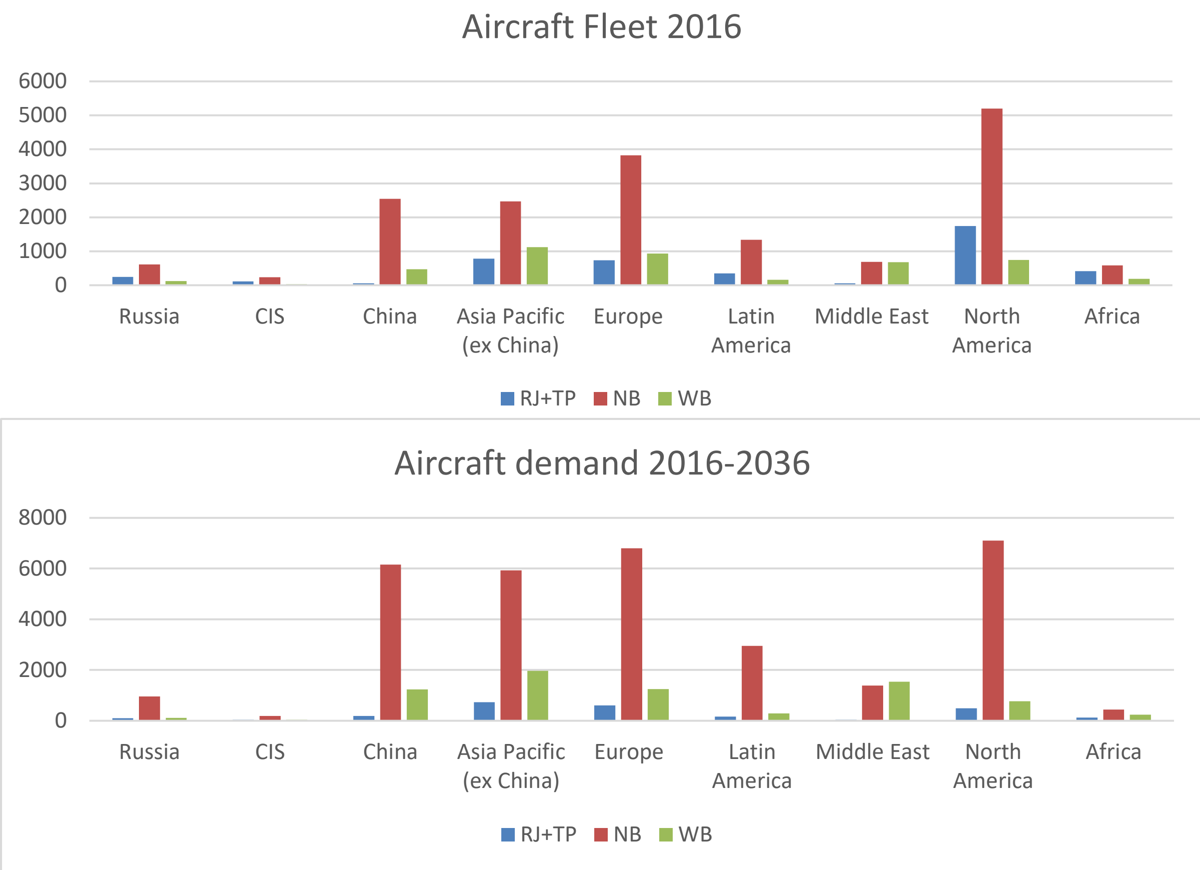


Figure 13.42. UAC aircraft demand forecast.[2]

13.2.5.5 The Airline Monitor Commercial Aircraft Market Forecast 2017 – 2040

The Airline Monitor (AM) is a leading source of information regarding airline performance, air traffic and aircraft production. It delivers twice in a year, in January and July, several reports that cover many different branches of commercial air transport such as aircraft production forecast (including forecasting by aircraft model), engine production forecast and prognosis regarding air traffic capacity and demand. Alongside the market forecast reports, AM offers an updated database that includes historical orders and deliveries data and airline performance by region (utilization time, mean speed, load factor…).

AM market forecast is divided into two different approaches. First, a macro-level approach of the aircraft fleet is calculated based on the air traffic prognosis by region. Using the airline performance data and projections, the world fleet is estimated using an average-sized aircraft. This average-sized aircraft number of seats is based on the mean of the actual world fleet's number of seats, which rounds 190. Thus, the forecast yields the number of aircraft that will be necessary to cover the demand of air transport in the following years, attending to a continuously improved airline performance over the time: this is, higher load factors and better aircraft utilization (higher block times and speeds).

The Airline Monitor traffic forecast considers six major regions on the world: Europe, CIS, Africa, Middle East, Asia-Pacific, North America and Latin America. The main macro-level driver considered

[2] RJ: Regional Jet; TP: Turboprop; NB: Narrow-body; WB: Wide-body

for this forecast is the GDP growth rate, which is directly proportional to the traffic growth rate per year. In order to get the traffic forecast formula, the GDP growth rate per year is multiplied by a factor that rounds 1.5 for the regions where aviation is a more extended mean of transport, and 2.5 for regions with higher growth perspectives such as Asia and the Middle East. The air traffic prognosis is presented in Figure 13.43. Emerging regions like Asia-Pacific or Latin America will almost quadruple its air traffic, with high growth rates rounding 6% per year. Regions where air transport has experimented a bigger development over the last two decades, like Europe or North America, are the ones with the lowest growth rates. Despite all these differences between regions, the Airline Monitor forecasts the world traffic to almost triplicate by 2040, with an average yearly growth of 5.1%.

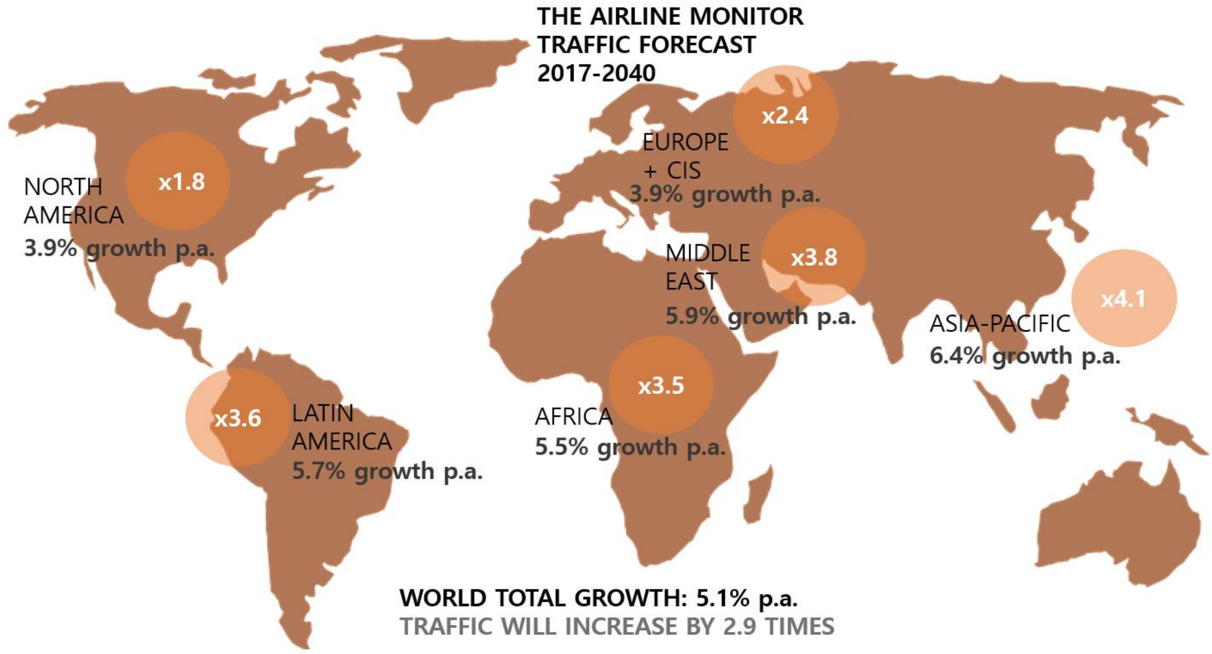


Figure 13.43. The Airline Monitor traffic forecast.

Using this traffic forecast, the Airline Monitor calculates the necessary world fleet (based on an average-sized, imaginary aircraft) to cover the demand for air transport. The fleet size estimations made are presented hereafter, in Figure 13.48.

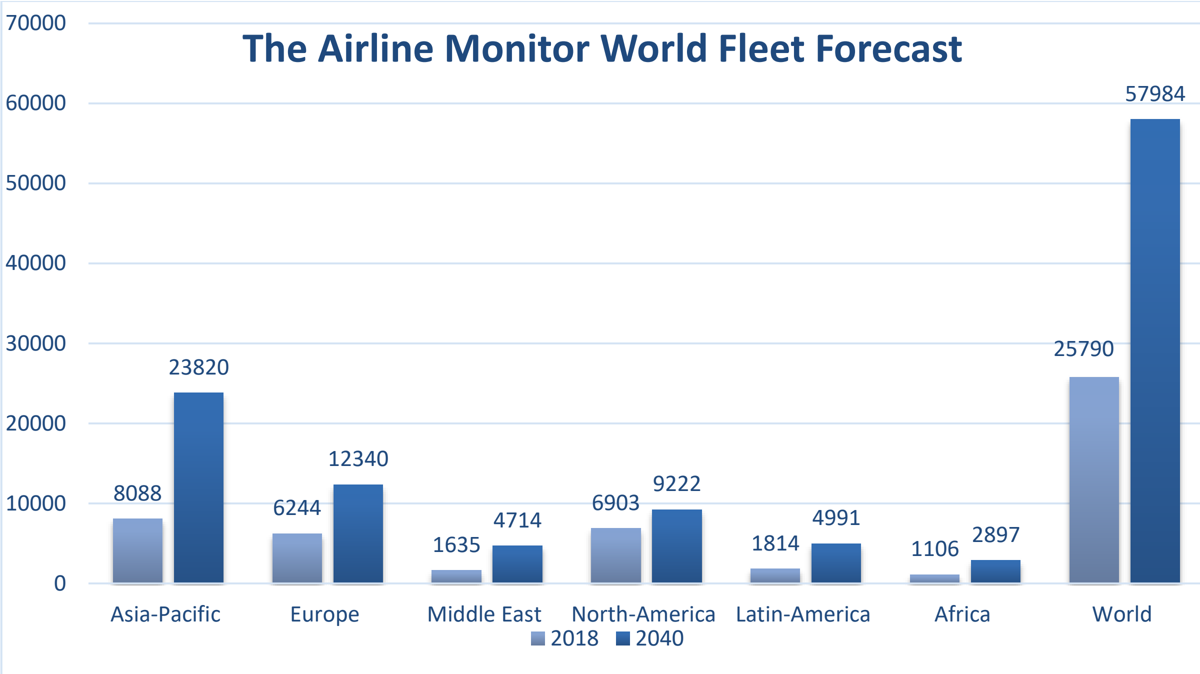


Figure 13.44. The Airline Monitor World Fleet Forecast. Source: The Airline Monitor

The fleet forecast shows a smaller growth rate in the number of airplanes than in passengers' turnover (RPKs). For example, for the Asia-Pacific region, the growth rate specified by the AM in terms of RPKs is about 6.1% per annum, whereas the fleet size is expected to grow at a yearly rate of 5.3% per year. This is due to the better performance of airlines regarding aircraft utilization and load factor. The airline monitor forecasts the load factor values to increase from 81.7% in 2018 to reach 84.0% in 2040. This improved utilization is due to better management of air routes and airport slots so that airlines can do better planning of their fleet. Airline performance data has been used as a baseline for PARE's Middle of the Market forecast and it is presented in the Annexes alongside the forecast methodology.

13.2.5.6 Comparative analysis of forecast hypothesis and results

In this section, the main hypotheses and results of every of the market forecasts discussed above are represented in a chart form, in order to highlight the main differences and assumptions that will serve to PARE's approach on Middle of the Market prognosis. The following chart lists the main hypotheses used, aircraft deliveries and retirements forecast by region by the kind of segmentation used, and air traffic average yearly growth rate by region.

A summary of the main conclusions extracted from each report is shown in Table 13.7, with the number of aircraft that will account the worldwide passenger aircraft fleet forecast by each of the publishers. Since the aircraft considered for the forecast and the hypotheses used differ one from another, it is necessary to take these discrepancies into account in order to integrate them into PARE's MoM forecast.

The fleet considered for the forecast differs from each author. For example, Airbus considers only western-built aircraft, with a total fleet of 19,800 airplanes by beginning 2018. The rest of the authors, on the other hand, use different fleet considerations that are not specified on their reports. In order to make proper comparisons between results, nominal values are used between brackets.

Regarding the hypotheses used, Boeing highlights the existence of increasingly airport congestion in the future, which will constrain airlines to improve fleet efficiency and to manage a better use of airport slots. From the published data, it can be concluded that Boeing believes in an increase of the average aircraft size in the future. This assumption is presented on the forecast's results since, despite predicting more optimistically the air traffic growth per year (4.7%) than Airbus (4.5%), the future fleet is forecast to be 1.9 times the actual one, as opposed to the 2.3 times multiplier of Airbus' forecast. This shows that Airbus believes in a dominance of the single-aisle segment as it has been occurring the previous years, representing more than half of the deliveries worldwide. On the other hand, Boeing believes in an increase of the wide-body aircraft demand, motivated by the infrastructural constraints and airport saturation.

13.2.6 Key market drivers for the MoM segment

When a new MoM aircraft enters this market, after 2025, the market would not be the same as today. The market will have grown by 100 million passengers in Asia alone and current aircraft will not be large enough to handle this growth. In addition, there is a large replacement market. Up to 40% of the market value is destined to the replacement of existing aircraft in this category, which is less suited for the job.

Aircraft are chosen by airlines to cover the routes they want to fly. Nevertheless, the opposite situation happens too. Over the last few years, aircraft with new capabilities opened some 400 new routes that existing aircraft did not be able to do because they did not have the economics. This will create a new fragmentation of the market. A good example of new routes opened thanks to new aircraft introduction is the new generation of long-range aircraft such as the Boeing 787 and the Airbus A350, which were able to open the longest routes ever seen in the market.

This chapter revises the main key driving forces influencing the evolution of air traffic, airplane production and evolution of the Middle of the market segment.

13.2.6.1 Fleet obsolescence and retirement

Large civil aircraft are typically used for 25 years or more before being sold to cargo fleets, non-scheduled carriers, or to foreign airlines that lack the resources to buy newer equipment. Some narrow-body passenger aircraft, including the DC-9, have flown in U.S. airline fleets for up to 40 years. The first Boeing 737s (the 100 and 200 series) was delivered in December 1967, 43 years ago. Because of the longevity of commercial aircraft, manufacturers must consider the entire life cycle of the plane in order to cover its development costs.

Historical data shows that more than 15,000 commercial aircraft have been retired worldwide in the past 35 years, with an annual retirement growth rate of more than 4% (Figure 13.45), a consequence of the growing global fleet. In recent years, about 700 aircraft are retired annually, with an average age of around 27 years. Currently, there are more than 27,000 commercial aircraft in service globally and the average airframe age is about 13 years, with more than 20% older than 20 years. It is estimated that 12,000 aircraft will be retired in the next two decades[31].

Publisher	Air Traffic Growth p.a.	Fleet count 2018	Fleet 2037 Forecast	Deliveries	Main hypothesis and considerations
Airbus	**4.5%**	**19,803**	**46,121** ***(x 2.3)***	**37,419**	• Wealth effect. Middle class growth stimulates traffic growth. • Low-cost business models are the main drivers of the future market
Boeing	**4.7%**	**24,400**	**48,540** ***(x 1.9)***	**42,730**	• GDP growth leads to more consumer spending that involves air travel • New liberalized policies (open skies agreements) will stimulate air travel • Airport congestion • Arise of low-cost long-haul business models
UAC	**4.6%**	**26,500**	**52,400**[3] ***(x2.0)***	**43,659**	• China and Asia-Pacific region as the main drivers of the sector
JADC	**4.5%**	**26,463**	**48,900** ***(x1.8)***	**33,530**	• Slight increment on crude oil prices • Increase of the worldwide middle-class and tourism • GDP growing lead by China
AM	**5.1%**	**26,042**	**52,578** ***(x2.0)***	**46,190**	• Air transport growth directly linked to GDP growth (with elasticity of 2.5 approx.)

Table 13.7. Forecasts' results and hypothesis summary

[3] Value not specified in UAC's report. Estimated value using the UAC's assumptions on fleet remaining [30].

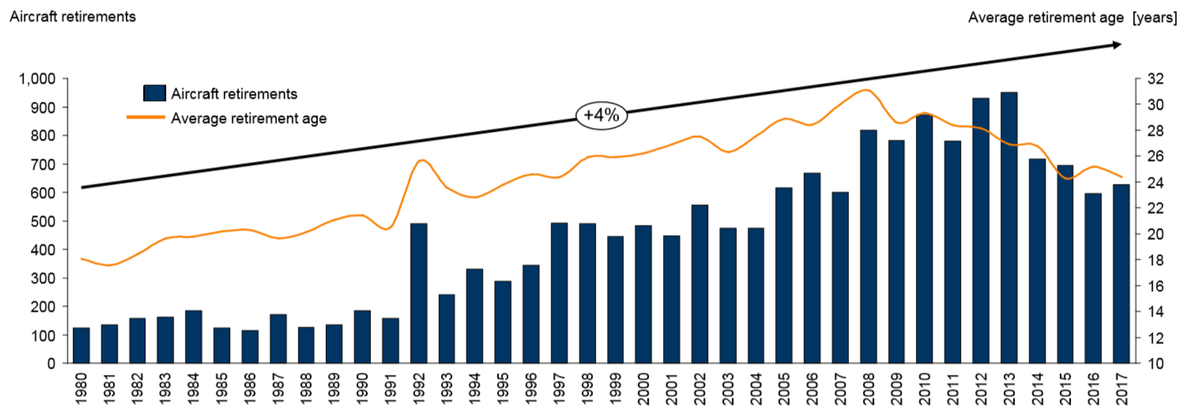


Figure 13.45. Historical aircraft retirements (1980-2017)

The distribution of aircraft retirement age from 1980 to 2017 is shown in Figure 13.46, indicating that the median retirement age for commercial aircraft over the last 36 years is 25 years, with more than half of the aircraft retired between the age of 20 and 30 years. On the other hand, Figure 13.47 shows the percentage of the retired fleet by ages. It can be seen that about 10% of aircraft were retired before the age of 17 years and about the same percentage were retired after 35 years of age. However, it is important to note that the first group consists mainly of small aircraft, while the latter is largely made up of freighters.

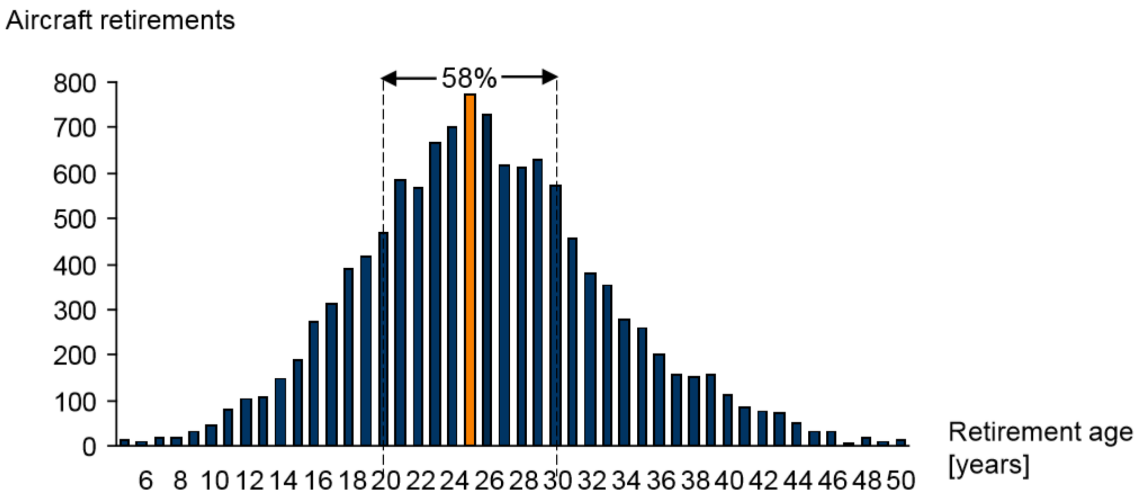


Figure 13.46. Aircraft retirement age distribution (1980-2017)[31]

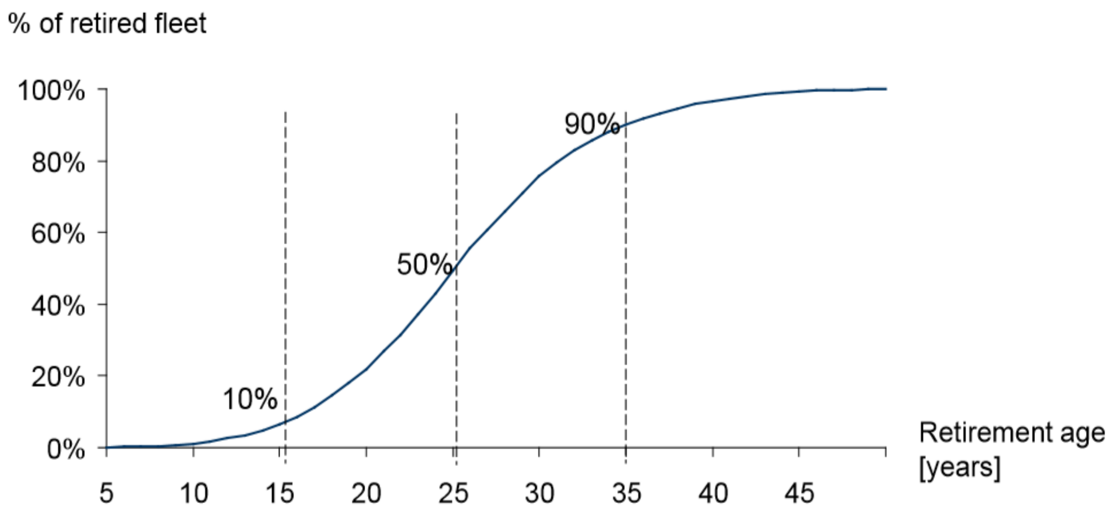


Figure 13.47. Percentage of the retired fleet by age (1980-2017).[31]

The historical data also shows different trends for narrow-body and wide-body jets. The average age of retirement for passenger aircraft is 28 years for the single-aisle segment and 25 years for the wide-bodies (Figure 13.48), which indicates that the most common retirement age yields between 20 to 30 years for both segments. It also shows that there are significant differences between passenger aircraft and freighters regarding retirement behaviours. Generally, freighters tend to be retired later than passenger aircraft, 38 years for single-aisle cargos and 31 for wide-body aircraft according to the figure.

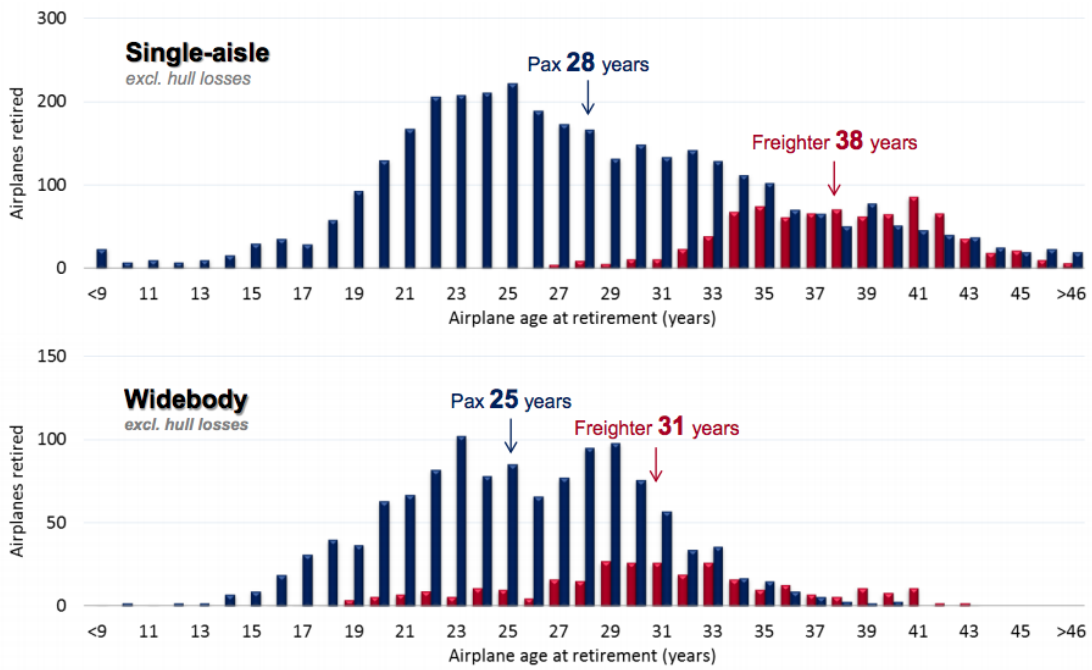


Figure 13.48. Wide-body and narrow-body trends in retirement. [32]

It is worth mentioning that conversion of passenger aircraft into freighters can extend the operating life of these aircraft. On average, this conversion takes place when the aircraft is about 18 years old, an age that coincides with a major structural aircraft heavy check. Typically, aircraft can gain 10 to 20 years of extra life by conversion. The incentive behind freighter conversions can be linked to the much lower utilization of freighters compared to passenger aircraft. Due to this utilization profile, freighter operators achieve a lower operational cost by extending the aircraft life cycle. In recent years, there has been an increasing trend to freighter conversions and a corresponding increase in the average conversion age.

Over the past decades, the world fleet of aircraft has slowly increased to more than 27,000 commercial aircraft operating worldwide, with an average age of about 13 years. As a result of the growing world fleet and lower average age, there will be an increasing number of aircraft removed from service and subsequently decommissioned in the upcoming years.

This is an essential factor to be considered for the MoM market, as several models of aircraft which operate this segment are aged and, as a consequence, many retirements are expected in the following years. Therefore, fleet obsolescence must be taken into account in this study, especially the case of the B757/B767 fleet. This fleet is no longer in production and there are few units in service nowadays. For this reason, the main objective of the new Boeing 797 is replacing this fleet and it is expected to be specially designed for flying the routes currently dominated by the B757 and B767 in a more efficient way, in terms of fuel consumption and operating costs.

13.2.6.2 Doubling the traditional 7 years' jetliner growth cycle

Jetliner market is today so strong that its cyclicality is often questioned. Since the beginning of the jet era, the market has followed a cyclic pattern: a growing period of roughly seven years followed by a dropping period of approximately three years with deliveries falling by 30-40%, or more in the bad period.

As can be seen in Figure 13.49, industry experiences a continuous growth since 2004, only slow down during 2016-2017 parenthesis (single-aisle deliveries pause before A320neo and 737MAX deliveries ramp-up). The expectations call for continued growth through 2020, at least [33]. Long-term demand drivers include a strong passenger traffic growth trend projected over the next two decades but a slowdown in market demand for new aircraft by carriers; industry OEMs (original equipment manufacturers) and industry value chain ramping up production to deliver on the huge accumulated order backlog. The 12,000 jetliners on the backlog at Airbus and Boeing alone is estimated to be worth over 7-8 years of production. The A320 family is on course for 60 planes per month, with the 737 headed for 57 per month. Boeing plans to raise 787 output from 12 to 14 per month in 2019. Airbus and Boeing both go to 70 single-aisles per month by 2023[34]. Considering these figures, for the very first time, the jetliner market will have a 16-year growth cycle, and possibly longer, over twice as long as the usual seven-year boom.

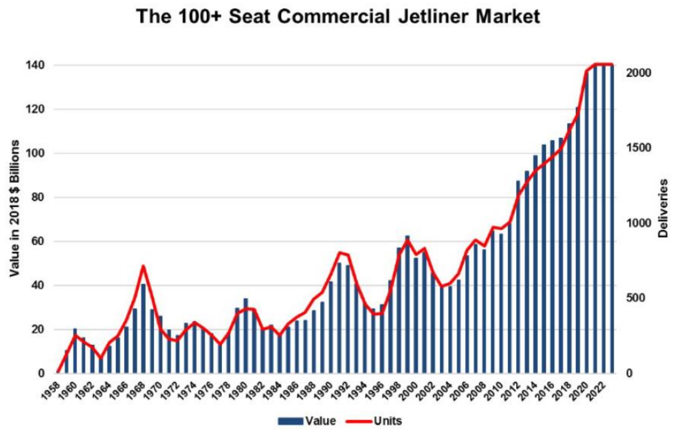


Figure 13.49. Airbus and Boeing jetliner deliveries history and planning.

13.2.6.3 The replacement of B757

The Boeing 757 is the largest single-aisle aircraft in the world, and it gives many advantages compared to bigger models. It is lighter, which allows flying longer distances without carrying too much fuel. Its capacity is good for ensuring a high load factor in scheduled flights. In addition, its take-off distance is very short, which allows it to operate in smaller, secondary airports. It is profitable in both short- and long-haul routes. Its only problem is that it is an old design, and current technologies can offer many more advantages. Both airlines and manufacturers have been discussing many options among the current line-up. For a more detailed description of the models discussed hereafter, the reader is referred to in Annex 1. Hereafter we briefly discuss substitution alternatives.

- **Boeing 737:** According to Boeing's chief officer, the new Boeing 737 MAX 9 covers 95% of the routes flown by the 757. Nevertheless, that fact is not sufficient to support that the 737 would be an adequate substitution. At first, Boeing was trying to stretch at maximum the potential of the single-aisle model in order to satisfy all the requirements. However, there is something where the 737 falls short: runway performance. The 757 can take-off at a speed of 140 knots using 4000 ft. of the runway, whereas the 737 needs about 160 knots and uses much more runway. In addition, the 737 requires a climbing procedure that burns much more fuel. The 757, instead, can comfortably climb to its cruising altitude. The plane is designed for another kind of mission, regional and short-haul routes.
- **Boeing 787-800:** Another potential substitute of the 757 can be the 787. Nevertheless, this aircraft is intended to operate in long-haul routes, so that operating it for the similar design mission as the 757 would be inefficient in terms of fuel burning.
- **Boeing NMA:** The new MMA should offer diverse advantages compared to the current Boeing 757, conserving its principal features. Short runway usage, about 220-280 passengers, 30-40% improvement in fuel efficiency with a maximum range of about 5000 nm.
- **Airbus A321LR:** The extended-range version of the longer narrow-body Airbus aircraft has a more conservative design, which leads to reduced risk. The main advantage of this option is that it is almost available now and it offers very good economics for medium-haul flights due to its single-aisle configuration. On the other hand, this configuration offers less comfortability to passengers due to the lower pitch between seats.
- **Airbus A330-800neo:** The new Airbus entrant in the Middle of the Market is the improved, re-engined version of the A330. Although it is designed for covering long-haul routes, it covers the upper layer of the Middle of the Market requirements.

In Section 13.2.4.2 "Boeing 757 and 767 stage length", analysis over the routes operated by the Boeing 757 was presented, showing the results of the average stage length flown by this model in 2018. The results showed that the aircraft is mainly used for transatlantic flights of distance less than 3000 nm, connecting mostly Europe and North America, mainly operated by Delta and American Airlines, the principal operators of this model.

Flow	Average distance	A321 LR	B737 MAX 9
Africa--North America	2950	100%	100%
Africa--South America	1484	100%	100%
Central Asia & Russia--China	1562	100%	100%
Central Asia & Russia--Europe	2144	100%	100%
Central Asia & Russia--Northeast Asia	2443	100%	100%
Central Asia & Russia--Southeast Asia	2763	100%	100%
Europe--Africa	2216	100%	100%
Europe--Central Asia & Russia	1677	100%	100%
Europe--Europe	1255	100%	100%
Europe--Middle East	1795	100%	100%
Europe--North America	2716	100%	73%
North America--Central America	1647	100%	100%
North America--North America	2082	100%	100%
North America--South America	2588	100%	71%
Central Asia & Russia--Central Asia & Russia	255	100%	100%
Central Asia & Russia--South Asia	893	100%	100%
Central Asia & Russia--Middle East	1184	100%	100%
Average	***1922***	***100%***	***89%***

Table 13.8. Boeing 757 single-aisle replacement options

The table above shows the regions connected by the Boeing 757 and the average distance of these routes. Additionally, the 'flyability' of these routes by the single-aisle replacement options is presented, showing the percentage of routes that the two models (A321neo LR and the Boeing 737 MAX 9) are able to cover. The analysis shows that the A321neo LR is able to fly the 100% of the routes covered by the B757 due to its extended 4100 nm range. Nevertheless, the drawback of the A321 LR is that carries 206 passengers (on a 2-class configuration and with 30 inches of pitch between seats), versus the 240 passengers that the stretched Boeing 757-300 can carry. The Boeing 737 MAX 9, on its side, is able to fly the 89% of the routes, carrying 192 passengers, 10 less than the Boeing 757-200.

There are many other factors apart from the range and capacity that have to be analysed in order to decide the appropriate substitution solution. Desai et al. [35] studied the profitability of every option presented above simulating several operation scenarios. The simulation evaluated the total profit obtained from the operation of the aircraft for different ranges and demands, varying from 2000 to 8000 passengers per week, and distances from 500 to 4000 nm. The results showed that the Boeing 737 MAX 9 was competitive in shorter routes with lower demands where airlines have to adapt their yield carefully. For longer routes and higher passenger volumes, the A321LR is a better option, whereas for passenger volumes higher than 7000 nm the best replacement options are wide-body aircraft such as the B787 and the A330-900, where the smaller single-aisle options cannot satisfy the demand. Additionally, there is a niche for shorter routes and passenger volumes between 6000-7000 passengers where the Boeing 757 is still the best option, and the new MoM aircraft is preferred for these scenarios.

	4000 Pax	5000 Pax	6000 Pax	7000 Pax	8000 Pax	9000 Pax
500nm	B737-900MAX	B737-900MAX	MoM	MoM	B787-900	A330-900
1000nm	B737-900MAX	B737-900MAX	MoM	MoM	B787-900	A330-900
1500nm	B737-900MAX	B737-900MAX	A321neoLR	MoM	B787-900	A330-900
2000nm	B737-900MAX	B737-900MAX	A321neoLR	MoM	B787-900	A330-900
2500nm	B737-900MAX	B737-900MAX	A321neoLR	MoM	B787-900	A330-900
3000nm	B737-900MAX	B737-900MAX	A321neoLR	MoM	B787-900	A330-900
3500nm	B737-900MAX	B737-900MAX	A321neoLR	B787-900	B787-900	A330-900
4000nm	B737-800MAX	A321neoLR	A321neoLR	B787-900	B787-900	A330-900
4500nm	MoM	B787-800	B787-800	B787-900	B787-900	A330-900
4500nm	MoM	B787-800	B787-800	B787-900	B787-900	A330-900

Table 13.9. Boeing 757 replacement options. Source: [35].

The routes analysis and the profitability evaluation made by Desai in [35] provides a useful set of information regarding Boeing 757 replacement options. The analysed options correspond to both narrow and wide-body aircraft families, which, depending on the mission, one or the other will be a better choice. This information is compiled and summarized in Table 13.10, showing the advantages and disadvantages of each of the options presented.

OPTION FOR REPLACEMENT	ADVANTAGES	DISADVANTAGES
BOEING 737 MAX -9, -10	Good economics for shorter routes and lower passenger volumes	Maximum seating of 192, lower than the B757's
BOEING 787-800	A better solution for stable demand and low frequencies	Not a good option for instable low demand on shorter routes
BOEING NMA	It can cover the niche between the narrow and wide-body aircraft offering better profitability	The gap could be very small in many situations
AIRBUS A321NEO LR	Fits the requirements on passenger seating and range in most of the cases	Maximum seat capacity offers less comfortability and could be not appropriate for longer flights
AIRBUS A330-800NEO	A good option for higher passenger volumes on longer routes	Not a good option for instable low demand on shorter routes

Table 13.10. Summary of replacement options for the Boeing 757.

13.2.6.4 The replacement of the B767

The Boeing 767 was designed as a smaller option than the 747 and it was introduced into service in 1981. Lately, a bigger version of the 767 was designed by Boeing resulting in the 777, the biggest twin jet in the world. The 767 can be considered as a medium-size wide-body jet and operates in the upper layer of the Middle of the Market, above the Boeing 757. By May 2018, around 302 Boeing 767s were operated by commercial airlines, as well as 382 in the freighter fleet. The average age of the Boeing 767 is 24 years worldwide, according to AirFleets [36]. The following graph shows the major operators of this model as well as the average fleet age by May 2018.

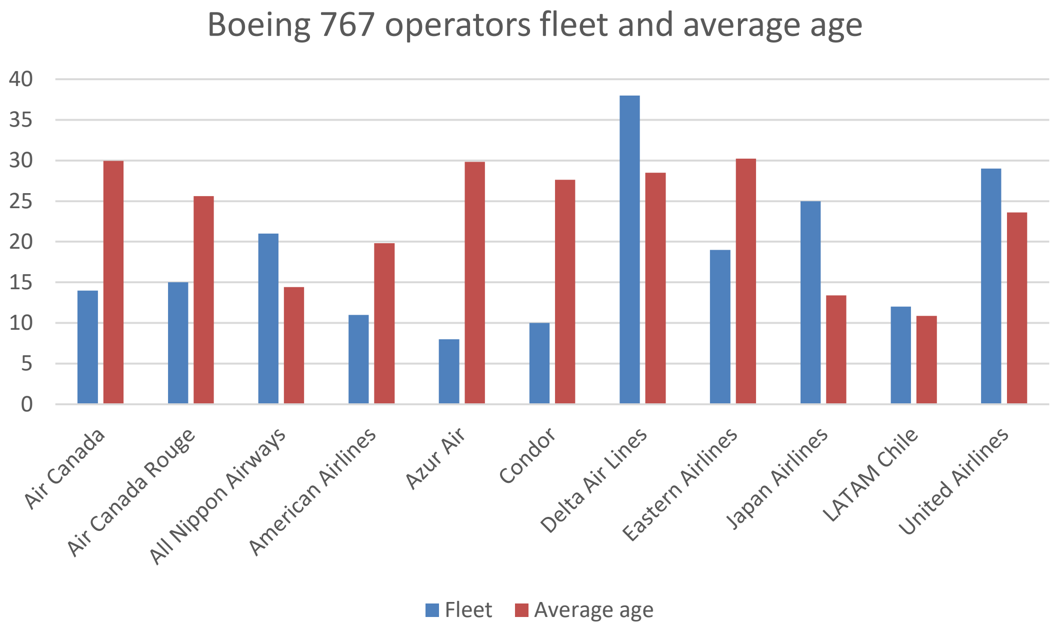


Figure 13.50. Boeing 767 major operators and fleet age.

The largest current operators of these mid-sized aircraft are the three US majors American, Delta and United, followed by the two largest Japanese airlines (All Nippon Airways and Japan Airlines) and the Canadians Air Canada and Air Canada Rouge, all of them with an average fleet age over 15 years.

Many discussions about the replacement options for this aircraft have arisen now that the end of the aircraft’s life is reaching its end, with airlines like Delta studying the possibility of ordering more than 200 aircraft to replace both the 757 and 767 fleets, according to SimpleFlying newspaper [37], focusing on Boeing’s NMA. American has committed to order more 787-8s to replace its remaining 767 fleet, and it will likely have replaced all 757s by the mid-2020s as well. Delta, thus, appears to be a key potential customer for a potentially new MoM aircraft, just as United, since it has not ordered a direct replacement for its 767 fleet yet, and it is considering the Airbus’ A330neo option, as well as the Boeing 787-9 since these two are the only options available at the moment.

It seems clear that airlines are focusing onto three different alternatives for a direct replacement of the Boeing 767. On the one hand, the newest Airbus A330neo, and its Boeing’s competitor, the Boeing 787-9 Dreamliner. On the other hand, Boeing’s proposal of a clean-sheet design for a new mid-size aircraft.

The following table summarizes the advantages and disadvantages of the airlines’ options for replacement.

OPTION FOR REPLACEMENT	ADVANTAGES	DISADVANTAGES
BOEING 787-900	Newer technology with less fuel burn than the 767.	Designed and optimized for longer routes.
BOEING NMA	Optimized for the mission of the B767.	Not announced and still uncertain.
AIRBUS A330-900NEO	Flexibility in the design, with lower MTOW and more thrust.	Excess of a range that results in a higher weight. Oversized for most of the 767 mission.

Table 13.11. Boeing 767 options for replacement.

13.2.6.5 Interactions in the Markets for Narrow and Wide-body Commercial Aircraft.

Both companies, Airbus and Boeing, have completed product lines that span all 100+ seat market segments. Decisions within one market segment are constrained by the state of products in other market segments. In the past, limited capital and engineering resources have prevented manufacturers from undertaking more than one major aircraft design program at any one time.

Conventional studies have neglected this complexity by assuming that manufacturers make a decision regarding the single-aisle market without constraints imposed by decisions regarding the twin-aisle market [38]. The competitive structure of the market for wide-body commercial passenger aircraft has been extensively explored by the literature because the market features several interesting analytic properties such as learning-by-doing, differentiated products, and active trade policy. Fewer studies have tackled the narrow-body market, much more complex and with much more actors [39].

Only a few authors have made some attempts to try to understand the dynamics and interaction between both markets, the narrow and wide-body commercial passenger aircraft markets, by investigating the competition between firms that produce only in the narrow-body market, and firms that produce in both the narrow and wide-body markets [40]. Additionally, there is evidence that suggests there may be cost linkages between developing small and large plane programs.

The analysis of the Middle of the Market segment extends the state of the art of competitive analysis because it implies the analysis of a segment that can be covered by models of each configuration. Boeing strategic proposal includes the adaptation of twin-aisle aircraft to serve the core part of the segment together with the enhanced configuration of the low range single-aisle models (737 MAX) as well as adaptations of upper range twin-aisle models (787-800). At the same time, Airbus considers that the MoM sector might be properly covered by the extensions of the upper narrow-body and the lower wide-body models.

For a proper analysis of the MoM, it could be necessary to consider multimarket oligopoly models. A simple approach can be taken from Bulow et al. [41]. When considering the purchase of an airplane, airlines can choose to either buy a single, large plane to fly fewer routes or buy multiple small planes which will run more frequently. This decision suggests that wide and narrow-body planes have strong interrelated demands. If a firm operates in two markets, a change in one market can affect the outcomes of the other market by changing competitors' strategic choices and by changing the firm's own marginal costs. Therefore, to understand better the commercial aircraft industry as a whole, it is necessary to explicitly study the wide and narrow-body markets together.

To account for the linkages between the narrow and wide-body markets, narrow and wide-body planes are normally considered substitutes for each other. This assumption deserves a little attention, though. When considering an aircraft for a route, the airline faces a choice of flying more passengers on fewer trips with a larger plane or few passengers on more frequent trips using a smaller plane. If there is sufficient traffic flow, then typically the former choice is more cost-effective from an operating standpoint. However, for airlines that have routes that are both long and short or have different volumes along with them, then it may be that the airline will purchase narrow and wide-body planes as complements. In the literature, only the substitution scenario seems to be relevant, though, so that this is the assumption made here.

13.2.6.6. Fuel prices evolution

The issues of reducing the cost of air travels and increasing the fuel-efficiency of existing aircraft and engines are among the priorities for commercial airlines. World leaders of air service work in close cooperation with companies that manufacture and upgrade engines and aircraft to achieve the highest fuel efficiency indicators.

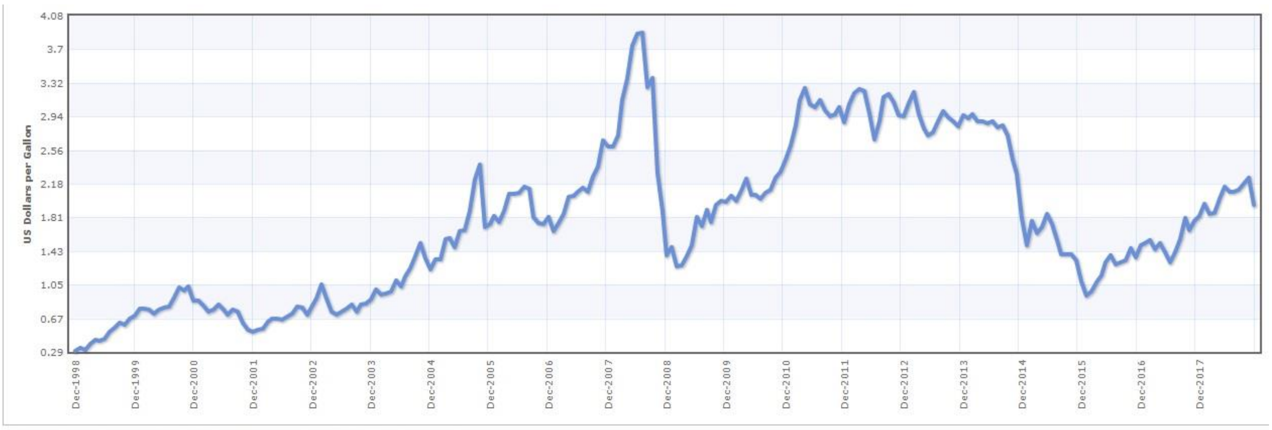


Figure 13.51. Change in fuel prices,1998-2018 [42]

The fuel price statistics over the last 20 years shows a relatively stable upward trend in prices since December 2001, with a peak in July 2008 (244% increase between July 2004 and July 2008). Thus, in December 2001, the price of 1 gallon was 52 cents, while in July 2008, 1 gallon cost was already 3 dollars and 89 cents, which is the highest price in the last 20 years. Over the next few months, fuel cost fell significantly, almost equal to the price level in December 2004, but by April 2011 the cost rose again to 3 dollars 27 cents per gallon, and over the next 4 years the fuel price was relatively stable with minor price fluctuations, till it fell to the level of 1 dollar 50 cents per gallon in January 2015. A further fall in prices continued until January 2016, but from February 2016 to the present day a steady increase in prices has been observed from 0,97 cents per gallon to 1 dollar 95 cents in November 2018. Thus, we have observed significant fluctuations in fuel prices that make air carriers dependent on oil production and the work of oil refineries.

Jet fuel prices are directly linked with crude oil prices. During the last 20 years, the price of the crude has been fluctuating from 20 $ a barrel as the lowest in beginning 2000, to 142$ per barrel as peak value in 2008, when the financial crisis took place, as it can be seen in Figure 13.52. The graph also shows that since 2015 the prices move steadily around 65-75$ per barrel but making oil price perspectives is a very difficult task due to the high number of factors involved. Geo-political decisions directly influence oil prices, that, inevitably, manifest on jet fuel prices and so it does in airlines' operating costs. The following graph shows the crude barrel prices evolution from 1999 to nowadays.

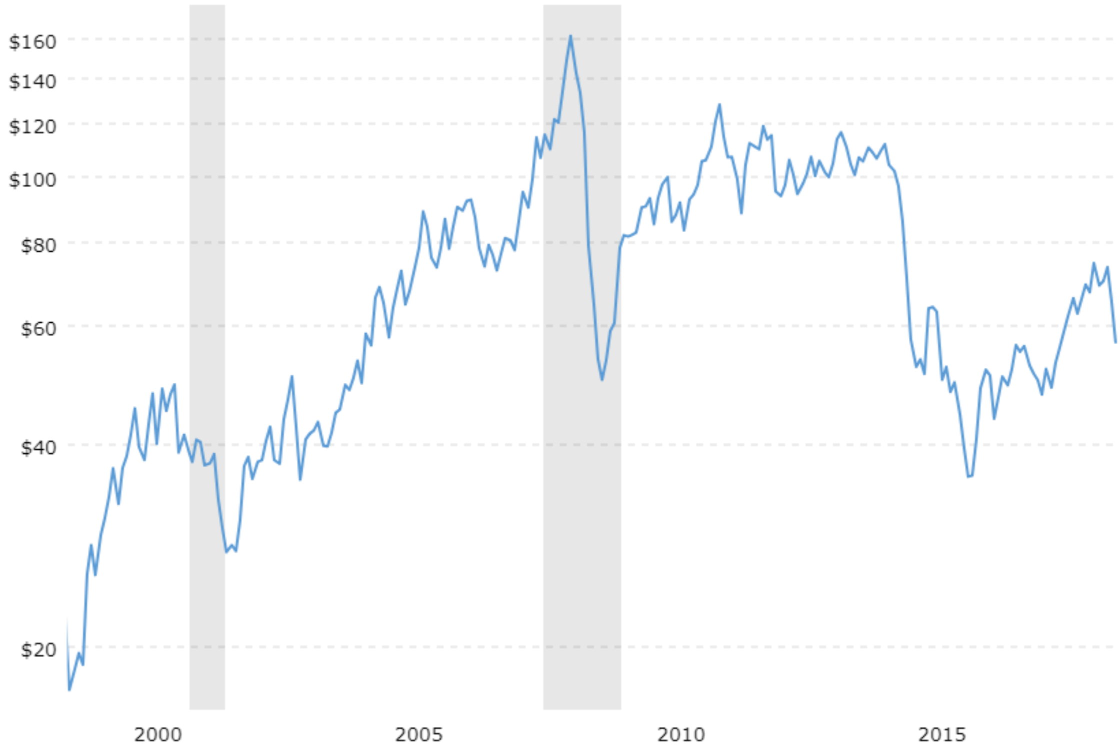


Figure 13.52. Oil barrel price evolution 1998-2018. [43]

According to IATA statistics, the share of aviation fuel costs ranges from 22.2% in 2005 to 35.6% in 2008 of the total costs. In 2008, the airlines' fuel expenses represented around 35% of the total operating cost, whereas in 2018, due to the reduction of the oil prices, it rounds 20%. Since 2012, a gradual decrease in the percentage of fuel costs has been observed from 33.2% in 2012 to 18.8% at the end of 2017. Fuel consumption by commercial airlines will grow annually to 2025 from 19% to 26%. For low-cost carriers, the percentage is even higher due to the cost reduction in the other areas. Between 2016 and 2017, Ryanair reported fuel costs of around 37-40% of its total expenses.

With peak oil theory predicting continued volatility and increasing costs of fossil fuels while new environmentally driven charges expecting to further add to fuel costs, the expectative of the industry are put in the improvements of fuel efficiency [44].

13.2.6.7 Fuel efficiency evolution

In the short and medium-term, increases in fuel costs translate into the higher operating cost. This can only be compensated in the long term by improving fleet fuel efficiency. The continuous increase of fuel efficiency of the aircraft currently in service and plan for entry into service is provided mainly by the development of the aircraft industry and the introduction of new technologies. Aircraft in service, as well as just designed aircraft, can be upgraded. It should be noted that aircraft in service will not always have a high rate of innovation, taking into account the fact that some of the improvements can be made only at the design stage.

Analysis evidenced that new jet aircraft have decreased their fuel burn by 70% between 1960 and 1997. According to some studies including Lee et al. (2001) and Peeters et al. (2005), the reduction in fuel consumption was about 64% and 55%[45], [46].

Other authors have quantified jet aircraft fuel efficiency historical improvement at a rate of 1.2-2.2% per year on a seat/km basis. However, fuel efficiency improvements have not been sufficient to counter increased emissions due to rising demand for air transport[46].

About 40% of the improvement has come from engine efficiency improvements and 30% from airframe efficiency improvements. Successive generations of engine technologies have led to reductions in specific fuel consumption, as shown in Figure 13.53.

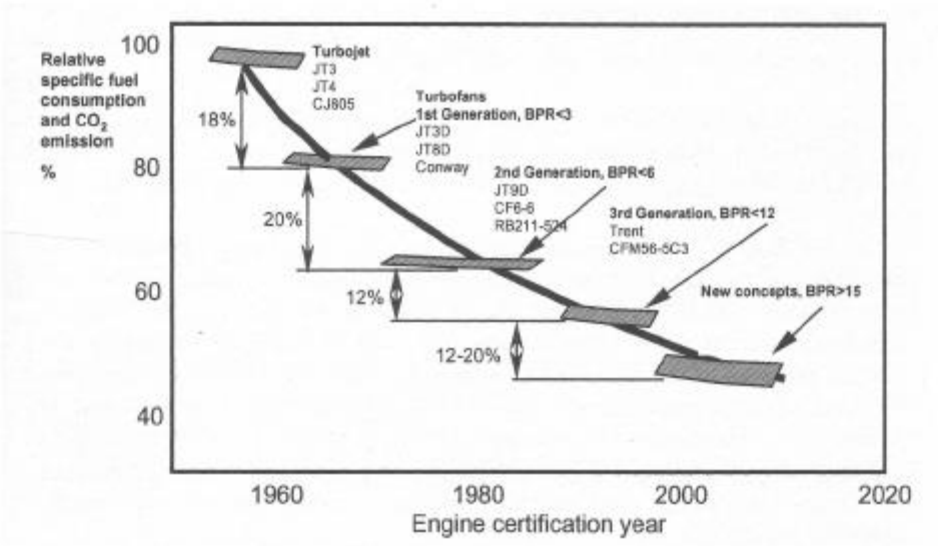


Figure 13.53. Reduction in fuel consumption and CO2 emissions by Engine Technology Source

The age of production line directly affects to the fuel efficiency: introduction of new technologies allows improving the parts manufacturing process, reducing fits and clearances, and, therefore, getting a gain in the final fuel saving. The ICC (International Council on Clear Transportation) 2008 study calculated the relationship between the age of the production lines of the engine section and the aircraft section (see Figure 13.54). The average age of the production lines of major global aircraft manufacturers (Airbus, Boeing, Bombardier, and Embraer) has tripled between 1990 and 2008. Since over the long-term most of the aggregate efficiency improvements for new equipment are expected to come from the commercialization of new, more efficient aircraft and engines, this trend helps to explain the falling rate of improvement over time. It should be noted that an average production line age of engines is slightly higher than that of aircraft. By the early 1970s, the difference in the age between production lines of engines and aircraft was only 2 to 3 years, while as of 2008, the gap was more than 10 years.

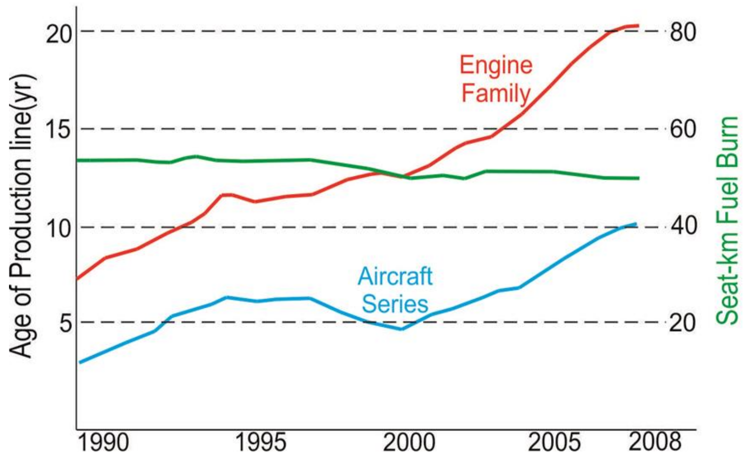


Figure 13.54. Diagram of the age of production line of aircraft versus engines, 1990 – 2008 [47]

The updated 2014 study of ICCT estimates higher average nominal fuel burn values, while maintaining the overall trend, as illustrated in Figure 13.55, where the fuel consumption value for the 1960s is taken as the baseline.

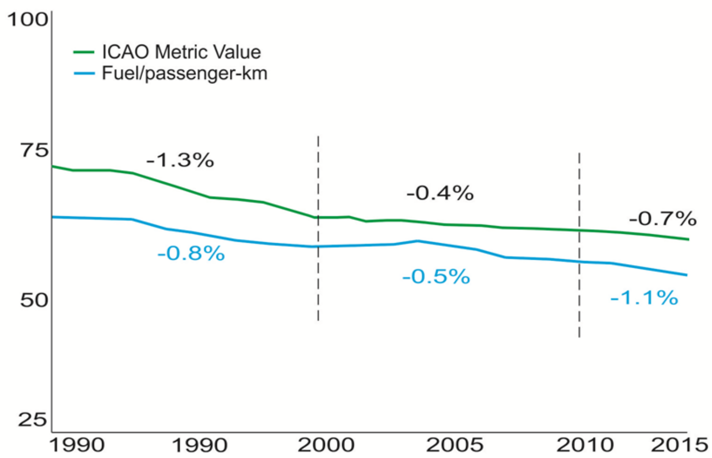


Figure 13.55. Diagram of the fuel-burn evolution, 1990-2015[48]

However, reductions in average aircraft fuel consumption slowed noticeably after 1990 and largely halted around 2000. After 2010, average fuel efficiency began to accelerate and has returned to the long-term average improvement of 1.1% per year. Acceleration in improvement rate began due to the introduction of new, more efficient aircraft designs such as the A320neo, 737 MAX, and 777X.

ICAO estimates the improvement potential in fuel efficiency in the order of 40% for new single-aisle and small twin-aisle aircraft in 2020 compared with 2000. Other more conservative researchers state that the average aircraft fuel efficiency has improved by only ~50% since the first jets, while efficiency gains have slowed to 0.0% since 2000, as shown in the figure. Analysis correlation between fuel cost and fuel efficiency by these same authors conclude that fuel cost has not been sufficient to stimulate increase aircraft efficiency.

As per today situation, Figure 13.56 compares the average fuel efficiency for each aircraft type, simulated using Piano 5 and FlightGlobal database. The Airbus A330 family of aircraft was the most widely used on transatlantic routes, accounting for 25% of all flights. Its fuel efficiency was approximately 1 pax-km/L better than the industry average. The Airbus A350-900 and Boeing 787 Dreamliner were more fuel-efficient with average fuel efficiencies at or above 40 pax-km/L. When the aircraft take-off mass increases, fuel efficiency declines. Aircraft with four engines are less fuel-efficient than those with two.

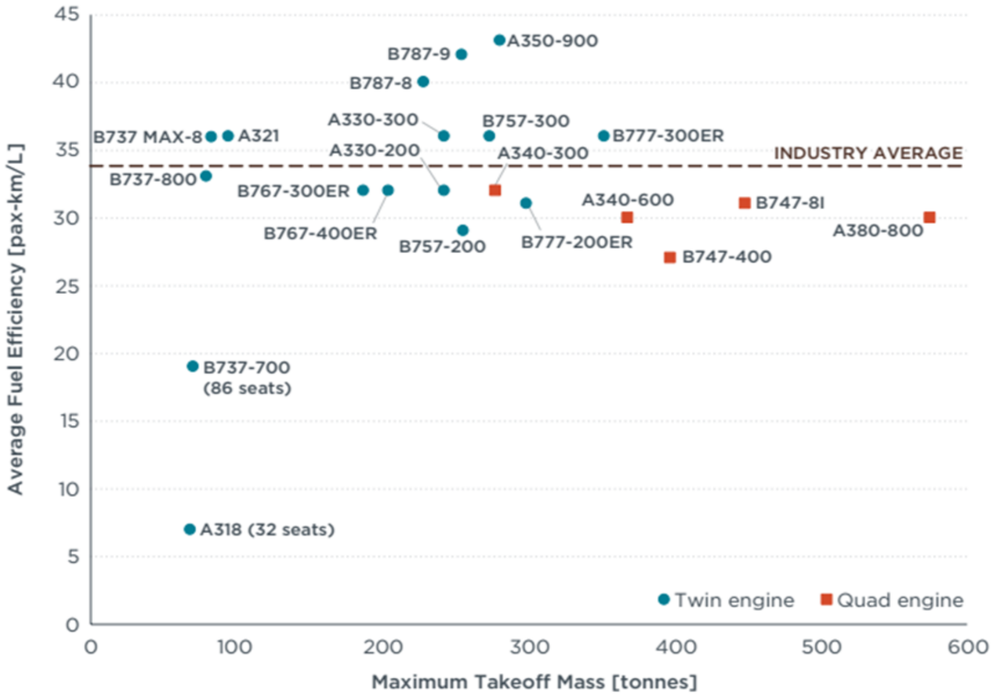


Figure 13.56. Diagram of fuel efficiency vs. maximum take-off mass of aircraft on transatlantic routes

13.2.6.8 Technologies to improve fuel efficiency, others than engines.

Reducing fuel consumption on modern aircraft can be achieved by investigation and implementation of new technologies into production. The range of research being conducted is quite wide. All aircraft systems are subject to improvements. Engineers and scientists are continuously struggling to reduce the weight of the structure, increasing the wing lift, while reducing the final weight of each aircraft system as well as maintaining its fail-operational capability and reliability. This concerns not only the systems providing aircraft operation, take-off or landing, but also the systems providing passenger comfort and commercial attraction of the flight as a whole.

In addition, ecologists are concerned about the increase in the share of emissions from commercial aircraft; this is another incentive for the development of fuel-saving technologies. Furthermore, new ICAO standards for permitted noise levels of the aircraft, whose take-off weight exceeds 55 tons, came into operation on December 31, 2017. This is an additional incentive for aircraft manufacturers, pushing them to introduce and develop technologies that reduce fuel consumption by aircraft engines since the level of noise produced directly depends on the amount of fuel consumed[49].

ICAO's CO_2 emission standard rewards technologies that reduce fuel burn. ICAO has estimated that achieving the targets for CO_2 emission reduction requires an annual fuel efficiency improvement by 2%. Assuming that the metric value reduction persists, it can be concluded that industry is lagging behind both the 2020 and 2030 ICAO goals by approximately 12 years. Given this trend, it appears unlikely that ICAO CO_2 targets can be achieved without additional support from governments. Any CO_2 emission standard should ensure additional emission reductions by taking into account the baseline level of industry improvement; also, it is necessary to avoid setting a standard that would be overtaken by "natural" improvement. Even if the adopted standard is stringent enough to incrementally improve fuel efficiency beyond the usual level, a supporting measure may be needed to promote structural efficiency, including the use of lightweight materials and the increase in aircraft design efficiency. Differentiated handling fees based on the fuel efficiency of in-service aircraft is one potential incentive[48].

At the moment, the aviation industry needs new technological solutions and materials that can reduce the weight of an empty aircraft while providing the necessary strength standards. The most promising ones are discussed here after.

Integrated configuration

One of the promising areas of aircraft development is the introduction of an integrated configuration of the airframe. This will reduce the fuel consumption of production aircraft by increasing wing efficiency. It is also expected to reduce noise due to the concealment of the power unit by airframe.

However, along with the advantages, there is a number of unsolved problems. The first one is the instability and poor control of this type of aircraft due to the absence of empennage. This problem is partially solved by the fly-by-wire control system, which is already widely used on aircraft of classical aerodynamic configuration. Aircraft with an integrated configuration is widely used in the military sphere. The main advantage of this airframe design for the military is the reduction of its radar visibility. Moreover, power plants with thrust vector control have already been worked out and tested on such aircraft, which partially helps to solve the problem with aircraft controllability. In addition, it is important to note that increased requirements for reliability and flight safety are set for passenger flights. In any case, the transition to the integrated configuration will not be instantaneous. According to the IATA technology roadmap, the gradual introduction of this technology will begin after 2020, followed by subsequent introduction after 2028.

The expected decrease in fuel consumption from the introduction of an integrated configuration will be about 10-15%.

Winglets

Drag reduction is one of the most important tasks for scientists and engineers. Drag is the aerodynamic force that opposes the forward motion of the aircraft. Drag is created not only by the frontal part of the aircraft but also by the fuselage as a whole. Efforts are taken to design the aircraft in such a way as to minimize the drag, but modern aircraft are huge, flying at high speeds, and therefore drag reduction is still one of the most important factors taken into account when designing modern aircraft [50].

The main method of drag controlling is to provide aerodynamic shape to all streamlined parts of the aircraft. This is done to prevent flow breakdown at the trailing edge of the wing and the fuselage in order to ensure more smooth airflow along with them. The wing is still the most important component of almost all aircraft, it is not surprising that research to improve its efficiency is still in progress. In addition to reducing the total weight of the wing, its efficiency can be increased by reducing the wing tip spill over.

This is achieved by the installation of special devices: winglets. The essence of their work is that when air flows around the wing of the aircraft, vortices appear on its tips, and their formation is caused by mixing of the air flowing over the wing with the air flowing under the wing, which provokes a decrease in lift and efficiency of the wing as a whole. Increase of final weight of the wing is a negative factor in the process of winglets installation. It is also necessary to consider the wingspan because hangars at airports and service platforms are often designed for the final wingspan of a particular aircraft and winglet installation will require solving this problem. The tips operate not in all power ratings and the entire duration of the flight; the most effective solution is to use them during long-haul flights. In addition, the winglets are an additional vertical plane, which will increase the influence of the crosswind when landing.

The overall gain in fuel saving from the installation of winglets is about 1-6%.

Auxiliary power units (APU)

Another important direction in the development of fuel saving is the installation of auxiliary (additional power) units. As a rule, an auxiliary power unit is a low-power engine, which provides the generator operation for supplying power to airborne systems when the main engines are not operating. In addition, some airports provide direct power supply to the aircraft, which also contributes to a decrease in fuel consumption and CO_2 emissions. Manufacturers of auxiliary power units are constantly working to improve their efficiency.

Since 1960, the power generated per kilogram of power unit weight has almost doubled, with a decrease in fuel consumption for more than 40%. In the near future, manufacturers will continue to improve the APU, more and more lightweight composite materials will be introduced into their design, leading to even greater weight loss and increase in power generated per kilogram. Also, the APU will be integrated with other aircraft systems, which will lead to an increase in their efficiency, as a result.

The overall gain in fuel economy from improving the APU is from 1 to 3%[50].

Fuel cells

In the long term, manufacturers are considering the option of replacing the APU with high-efficient fuel cells. This fact will allow eliminating completely the APU and supplying power to airborne systems from the fuel cell. In general, any fuel cell has 2 electrodes, anode and cathode, between which the reaction takes place, producing an electric current. Hydrogen is used as a fuel, but fuel cells also require oxygen for the reaction to proceed. However, cells can also work from an external source of chemical energy (hydrogen and oxygen), while they are not exhausted as lithium batteries and with sufficient supply of chemical elements can function almost infinitely. In the course of a chemical reaction, combustion does not occur. The oxidation of hydrogen is a very efficient electrolytic process. During the reaction, the hydrogen atoms interact with the oxygen atoms, the electrons are released and flow through the external circuit as electric current, the result is a harmless product, ordinary water.

Fuel cells are quite diverse; among them, there are small devices that produce only a few watts of electricity, and large units capable of producing megawatts of electricity. The principle of operation of all fuel cells is based on the current flow between two electrodes, separated by a solid or liquid electrolyte, which carries electrically charged particles between them. Catalysts are commonly used to accelerate the reaction. Fuel cells are classified according to the nature of the electrolyte used. Different types of cells require different materials and different types of fuels used in each specific situation.

Fuel efficiency improvement makes up 1-3%.

Composite materials

Another important element of the aircraft, requiring weight reduction, is the fuselage. It is the aircraft construction base, which bears the weight of all flight support systems, payload, fuel load, etc. Being the most massive part of the aircraft, it has the greatest potential for weight reduction with a constant strength. Another important factor is a weight reduction of aircraft systems, for example, lighter carbon brakes, which replace the steel brakes, can save up to 250 kilograms. Options for all-electric brakes are also considered, as they are lighter, their condition is easier to control, and also hydraulic or pneumatic power supply is not required.

According to the report of Alan Miller, director of technology integration for the Boeing 787 program, the percentage of composite materials used in the Boeing 787 reaches 50%. The main elements such as fuselage, engine nacelle and controls are made of composites. At the same time, some critical parts remain metal: engine attachments, leading edges of the wing and empennage.

A few days before the Dreamliner's first flight, Boeing published a document for airlines. Its essence was that the take-off weight of the aircraft exceeded the design weight by 9.25 tons in comparison with the stated two years earlier. Airlines ordered 840 aircraft, based on Boeing's forecasts for speed, range, payload and fuel saving; all these indicators were decreased by the additional weight. Mike Delaney, the chief engineer of the 787 project, assured that the Dreamliner will still achieve its planned performance and, according to initial forecasts, will become more efficient by 20% in comparison to previous Boeing models. The problem of weight reduction was intensified on the 787 model when Boeing engineers discovered a structural defect in the attachment of the wing to the fuselage and had to strengthen these components with titanium fittings. The only detail that Boeing does not disclose is the empty weight of an aircraft. This situation is quite common.

The last 25 years of the development of aviation industry show that aircraft will also become lighter due to weight reduction in aircraft interior. The intensity of aircraft utilization enables to make modifications only at the stage of scheduled maintenance, especially with regard to components of large aircraft subsystems, such as lighting, fuel and electrical systems. Regular maintenance allows identifying and correcting minor defects, such as scratches, chipped paint, which ultimately leads to a fuel saving of about 0.5%.

Soon, new types of paints will become available, their weight is expected to be 10-20% lower compared to the currently available analogues. New coatings that will be more resistant to scratches and fractures are also under development. Some companies have begun to use a new method of painting the aircraft, which eliminates the need to cover the aircraft with a 3mm layer of paint, which saved about 136 kg of paint and reduced the final weight of the aircraft.

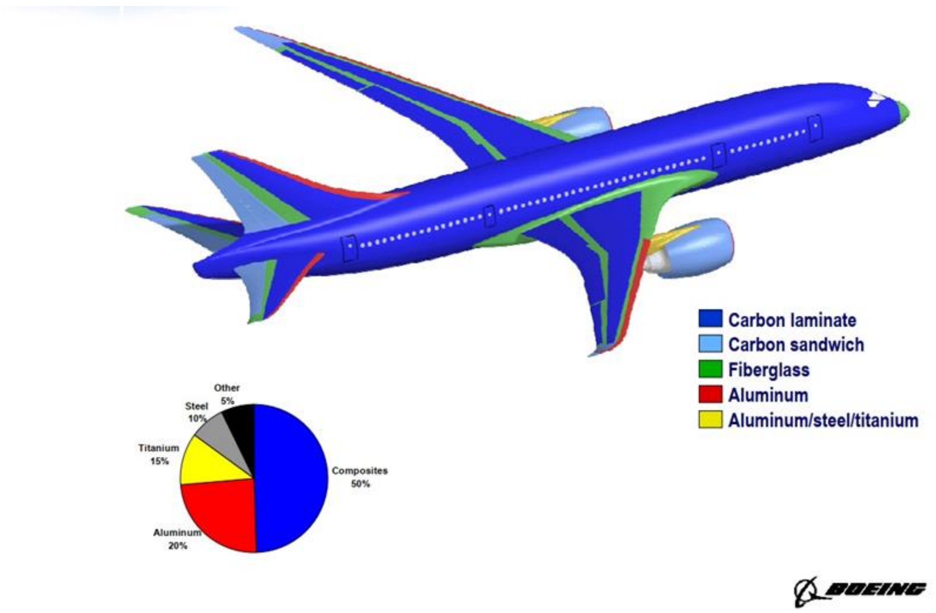


Figure 13.57. The percentage of composites used in Boeing 787 design

Optimizing the route network

The optimization of the traffic logistics also contributes to fuel saving. Air carriers strive to optimize their rout workload to the full extent to increase the efficient use of fuel. The workload of various routes is a function of many factors, seasonal factors playing a decisive role: vacations, holidays, specific events of global scale like the Olympic Games or the World Football Championship. More flexible use of the aircraft fleet allows air carriers to adjust to specific tasks, and to optimize long and mid-range flights. New route optimization methods can also contribute to the increase in passenger number per flight, and thus reduce the amount of fuel per passenger. In addition, pilots receive more information about the wind velocity and direction, so they can adjust to present flight conditions. The aircraft centre of gravity plays an important role; the distribution of a slightly heavier load towards the back of the aircraft provides a significant gain in fuel saving (up to 0.5% per flight).

According to specialists, 8% of the fuel is lost due to inefficient flight routing by air carriers. With the intensification of passenger air traffic, the problem will have global effects[50].

Preparing for take-off

The development of precision navigation systems helping to reduce route deviations is another method for increasing fuel efficiency. Emphasis is put on the optimization of work of air navigation service providers (ANSPs) and the design of new take-off, cruise and landing procedures and routings which take into account fuel saving factors. A number of airports and airlines are implementing the so-called ‘green departures‘, allowing pilots to take-off and climb to the optimal cruising altitude in one smooth, continuous ascent. This resonates with existing methods of climbing to the cruising altitude in several steps. By using these new take-off and landing procedures at one airport alone, 10,000 tonnes of fuel were saved, and CO_2 emissions into the atmosphere were reduced by 32,000 tonnes in one year. Using satellite-based precision navigation systems such as “Area Navigation” allows re-designed aircraft to fly with the highest fuel efficiency between airports in the world. The optimization of the take-off and landing system has reduced departure delays of more than 2.5

minutes. Annual fuel savings are estimated at $34 million, with cumulative savings of $105 million from 2006 through 2008[50].

Smooth ride technology

Turbulence area, the lateral wind not only cause discomfort but also rise fuel consumption because of deviations from the course and excessive sinks. "Smooth Ride Technology" is designed to countermeasure those effects. The systems use a wide number of sensors and calculating units, which primary function is to monitor flight conditions and provide pilots with correct information on the current state of aircraft and the flight stage, as well as to maintain a stable course and altitude of the flight. Sensors around the aircraft measure changes in angular velocity and pressure distribution. Wind gusts that cause yaw, pitch or roll, for example, are detected and recorded by gyroscopic sensors. Similarly, vertical and horizontal forces on the craft are measured by accelerometers. At the same time, pressure sensors detect pressure distribution changes around the skin of the airplane through a selected (but unspecified) number of static air intake ports. Sensor data is then sent to a central processing unit that delivers electric signals comes via a fly-by-wire system to actuator devices. Special features of the Boeing technology are that the signal processing chain occurs, and the control action is generated before inertial forces set into action.

If, for example, a strong horizontal wind gust hits the aircraft, the system calculates the pressure differential across the vertical fin of the aircraft, then moves the rudder to counteract that gust. All of this happens before the aircraft's inertial response. The operation of this system, however, directly depends upon the data processing speed of the on-board computer and any slight delay causing a dramatic decrease in efficiency in the system. Using an improved fly-by-wire system will allow to gaining a fuel saving of between 1 and 3 %[51].

13.2.6.9 Environment regulations

The aviation industry has always been almost exempted from policies that force the use of a specific technology. Aircraft are made using technology that strictly satisfies safety requirements and due to that, most of the times the technology used is a step behind the available ones at the moment. Nevertheless, in a near future and due to the high growth expectations of the air traffic, it is possible that some regulations related to aircraft emissions and noise will be defined, and this will impact on the technology used by aircraft.

It is recognised that the contribution of aviation activities to climate change, noise and air quality impacts is increasing, thereby affecting the health and quality of life of citizens. These impacts are currently forecast to increase. Therefore, the ability of the aviation sector to grow is directly linked to how effectively it responds to the major environmental challenges ahead. Significant resources are being invested at the states level, as well as by industry, to address this environmental challenge. While improvements are being made across various measures (technology, operations, airports, market-based measures), their combined effect has not kept pace with the strong growth in the demand for air travel, thereby leading to an overall increase in the environmental impact.

Recent certification data demonstrates that advanced technologies continue to be integrated into new designs :

- New aircraft noise standard became applicable on 1 January 2018, and new aeroplane carbon dioxide (CO_2) and engine particulate matter (PM) standards will become applicable on 1 January 2020.
- The average noise level of the twin-aisle aircraft category in the European fleet has significantly reduced since 2008 due to the introduction of the Airbus A350 and Boeing 787.
- New technologies (e.g. supersonic and urban mobility aircraft) need to be carefully integrated into the aviation system to avoid undermining progress in mitigating environmental impacts.

Policies regarding Global Greenhouse Gases (GHG) and emissions

In 2016, aviation was accountable for 3.6% of the total EU28 greenhouse gas emissions and for 13.4% of the emissions from transport, making aviation the second most important source of transport GHG emissions after road traffic[52]. Emissions from aviation are therefore subject to the EU's domestic greenhouse gas emission reduction targets of 20% and 40% for 2020 and 2030 respectively, and they are thereby part of the EU's contribution to meeting the Paris Agreement objectives. Greenhouse gas emissions from aviation in the EU have more than doubled since 1990 when it accounted for 1,4% of total emissions. As emissions from non-transport sources decline, emissions from aviation become increasingly significant [53]. European aviation represented 20% of global aviation's CO_2 emissions in 2015.

Aviation is also an important source of air pollutants, especially of nitrogen oxides (NO_X) and particulate matter (PM). In 2015, it accounted for 14% of all EU transport NO_X emissions, and for 7% of the total EU NO_X emissions. In absolute terms, NOx emissions from aviation have doubled since 1990, and their relative share has quadrupled, as other economic sectors have achieved significant reductions. The carbon monoxide (CO) and oxides of sulphur (SO_X) emissions from aviation have also gone up since 1990, while these emissions from most other transport modes have fallen [53], [54].

According to the data reported by the Members States to the United Nations Framework Convention on Climate Change (UNFCCC), the CO_2 emissions of all flights departing from EU28 and EFTA increased from 88 to 171 million tonnes (+95%) between 1990 and 2016 (Figure 13.58). In comparison, CO_2 emissions estimated with the IMPACT model reached 163 million tonnes (Mt) in 2017, which is 16% more than in 2005 and 10% more than in 2014. Over the same period, the average fuel burn per passenger kilometre flown for passenger aircraft, excluding business aviation, went down by 24%. This has been reduced at an average rate of 2.8% per annum between 2014 and 2017.

However, this efficiency gain was not sufficient to counterbalance the increase in CO_2 emitted due to the growth in the number of flights, aircraft size and flown distance. Future CO_2 emissions under the base traffic forecast and advanced technology scenario are expected to increase by a further 21% to reach 198 Mt in 2040. The annual purchase of allowances by aircraft operators under the EU Emissions Trading System (ETS) since 2013 resulted in a reduction of 27 Mt of net CO_2 emissions in 2017, which should rise to about 32 Mt by 2020.

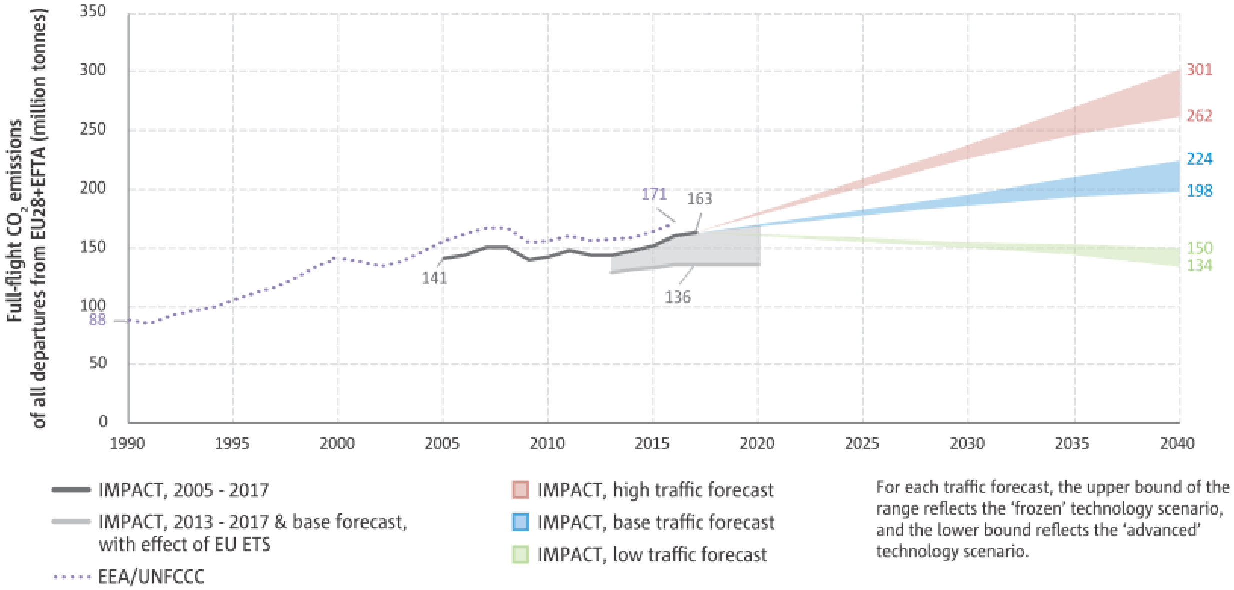


Figure 13.58. CO2 emissions are steadily increasing again since 2013

NO_X emissions have followed a steeper upward trend than CO_2 in recent years (Figure 13.59). They increased from 313 to 700 thousand tonnes between 1990 and 2016 according to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) data from the UN Economic Commission for Europe, and by 25% between 2005 and 2017 according to estimates from the IMPACT model. Unlike the CO_2 trend, current predictions indicate that the advanced engine NO_X technology scenario could lead to a downward trend after 2030. However, NO_X emissions would still reach around 1 million tonnes in 2040 under the base traffic forecast (+45% compared to 2005).

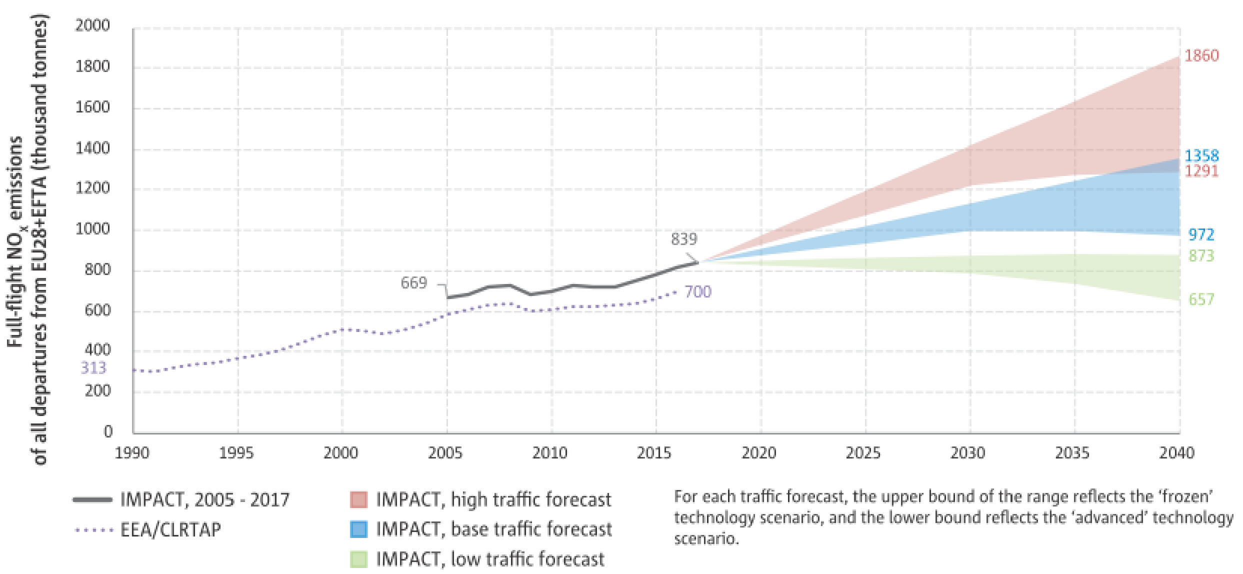


Figure 13.59. NOx emissions will increase further, but advanced engine combustor technology could help curb their growth after 2030

In 2010, EU and European Free Trade Association (EFTA) States agreed to work through the International Civil Aviation Organization (ICAO) to achieve a global annual average fuel efficiency improvement of 2% and to cap the global net carbon emissions of international aviation at 2020 levels.

During 2012, Member States submitted Action Plans to the ICAO for the first time, outlining their respective policies and actions to limit or reduce the impact of aviation on the global climate. Updated and extended State action plans were subsequently provided in 2015 and 2018. The latest global environmental standards were adopted by ICAO in 2017. These covers both aeroplane CO_2 emissions and aircraft engine non-volatile Particulate Matter (nvPM) mass concentration. EASA has subsequently supported the process to integrate these standards into European legislation [55] and will implement them as of the applicability date of 1 January 2020.

The CO_2 standard provides an additional requirement into the design process that increases the priority of fuel efficiency in the overall aeroplane design. It is an important step forward to address the growing CO_2 emissions from the aviation sector and will contribute to the climate change mitigation objectives of the UNFCCC Paris Agreement [56]. The nvPM mass concentration standard is expected to ultimately replace the existing Smoke Number requirement. ICAO is also working on future standards for both nvPM mass and nvPM number, which are based on the emissions that occur during landing and take-off operations. These proposed standards will be discussed at the CAEP/11 meeting in 2019. If agreed, it is expected that they will be implemented too into the European legislative framework.

EU air pollution legislation follows a twin-track approach of implementing both local air quality standards[57], [58] and source-based mitigation controls (e.g. engine emissions and fuel quality standards). Binding national limits for emissions of the most important pollutants have also been established in the EU, but not all aviation activities are included[59].

Noise regulations

The EU Environmental Noise Directive [60] requires noise action plans to be drawn up by the Member States addressing the main sources of noise, including aviation, with the aim of reducing the impact of noise upon populations. The first action plans were developed in 2008 and thereafter again in 2013 and 2018. Member States have identified a range of specific measures in their action plans to address noise from aviation-related sources. These include operational measures which reduce noise from aircraft operations (e.g. optimised flight procedures, airport night-time flight restrictions, charges for noisier aircraft), and measures focused on reducing noise at the receiver (e.g. sound insulation of houses). Out of the 85 major airports in the EU (airports with more than 50,000 movements in 2011), approximately two-thirds had adopted an action plan at the end of 2018.

The EU and EFTA have aircraft and engine environmental certification standards [61] which refer directly to the equivalent International Civil Aviation Organization (ICAO) standards [62]–[64]. ICAO's Committee on Aviation Environmental Protection (CAEP) is responsible for maintaining these standards.

Jet and heavy propeller-driven aircraft must comply with noise certification requirements and the associated noise limits referred to as Chapters 13.2.1, 13.2.2 and 13.2.11 [62]. These Chapters represent the increasingly stringent standards that have been agreed over time.

Figure 13.60 illustrates the differences between the noise certification standards with noise contours for four hypothetical 75-tonne jet aircraft that just meet the various Chapter limits. The contours represent areas that are exposed to noise levels greater than 80 dB during one landing and take-off and can be seen to reduce overtime from the first Chapter 13.2.1 "Objectives" standard applicable before 1977 to the latest Chapter 13.2.11 standard applicable in 2018.

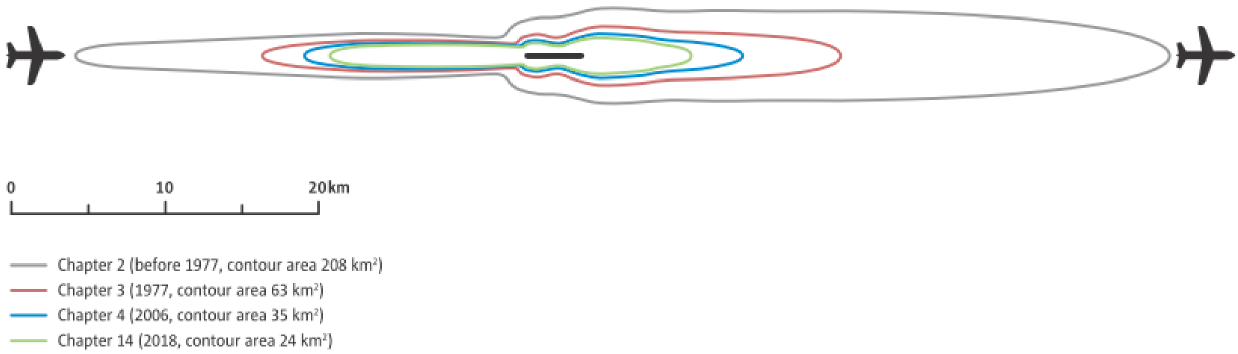
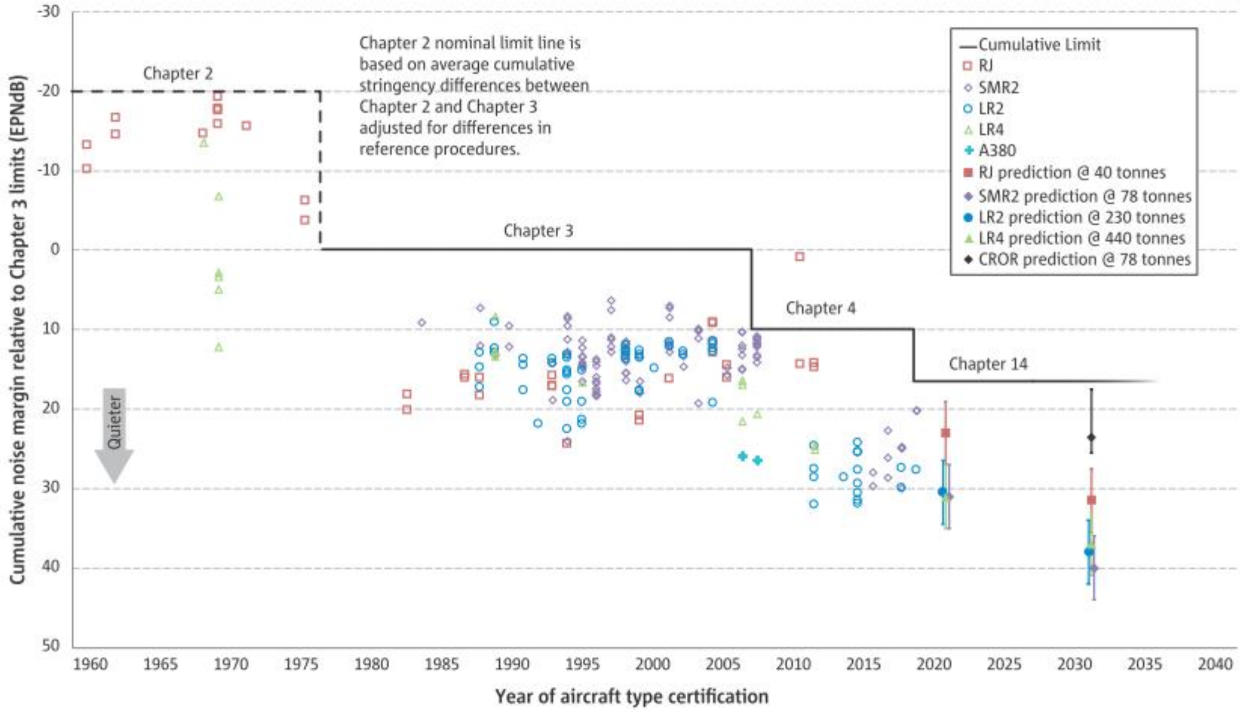


Figure 13.60. Single landing and take-off 80 dB noise contours for four hypothetical aircraft that just meet the noise limits of the various[62]

Figure 13.61 presents an overview of the improvement in aircraft noise technology design performance over time in terms of the cumulative 6 margin to the Chapter 12.2.1 "Scope" limits [64]. While recognising that aircraft are often sold in various configurations, the figure only contains data for the heaviest weights and maximum engine thrust ratings. As the associated noise limits are higher for larger, heavier aircraft, this figure permits a comparison between the relative performance across a range of different aircraft types. The data has been reviewed, and new aircraft noise levels that have been certified by EASA during the 2016 to 2018 period have been added. Although these latest additions have a similar margin to aircraft from the period 2010 to 2015, they are still well below the applicable limit.

A view on future development goals that illustrate which technology could be potentially achieved in 2020 and 2030, along with uncertainty bands, has been maintained in Figure 13.61. These are based on a review of noise technology by independent experts (IE) for the ICAO Committee on Aviation Environmental Protection that was performed between 2010 and 2013 [65]. The four categories cover most current jet aircraft families, except for the A380, which is added for information. An estimate is also provided for a small/medium-range aircraft powered by two Counter-Rotating Open Rotor (CROR) engines, which are expected to be able to just meet Chapter 13.2.11.

Figure 13.62 represents the average noise margin to the Chapter 13.2.1 "Scope" limit for all aircraft built in a given year that has been registered in the EU or EFTA after 2000. In order to illustrate the trend of technology purchased over time, the data is plotted by build year and displayed in five categories. Figure 13.62 shows that the margin to the Chapter 13.2.1 "Scope" limit actually decreases for regional jets, despite the general trend of improved aircraft type certification noise levels. This decrease in margin is primarily due to the market purchasing larger models and heavier weight variants (e.g. shifting from ERJ-145 to EMB-175 regional jets). The introduction of the Bombardier CS100 and CS300 aircraft in 2016, subsequently renamed the Airbus A220-100 and-300, appears to be responsible for the improved margin in that year. While the single-aisle trend has been relatively flat, the recent introduction of the re-engined Airbus A320neo and Boeing 737 MAX aircraft is expected to lead to future improvements in the margin. With respect to the twin-aisle category, the improvement in noise margin from 2008 is primarily associated with the introduction of the Boeing 787 and Airbus A350 aircraft types.



Aircraft categories as defined by ICAO/CAEP independent experts (IE)

	Description	MTOW (tonnes)
RJ	Regional Jet	30 - 50
SMR2	Short/Medium Range 2-engine	58 - 98
CROR	Counter-Rotating Open Rotor	58 - 91
LR2	Long Range 2-engine	170 - 290
LR4	Long Range 4-engine	330 - 550

Airbus A380 plotted for information as outside weight range for LR4 (575 tonnes)

Figure 13.61. Improvement in aircraft noise performance has occurred over time

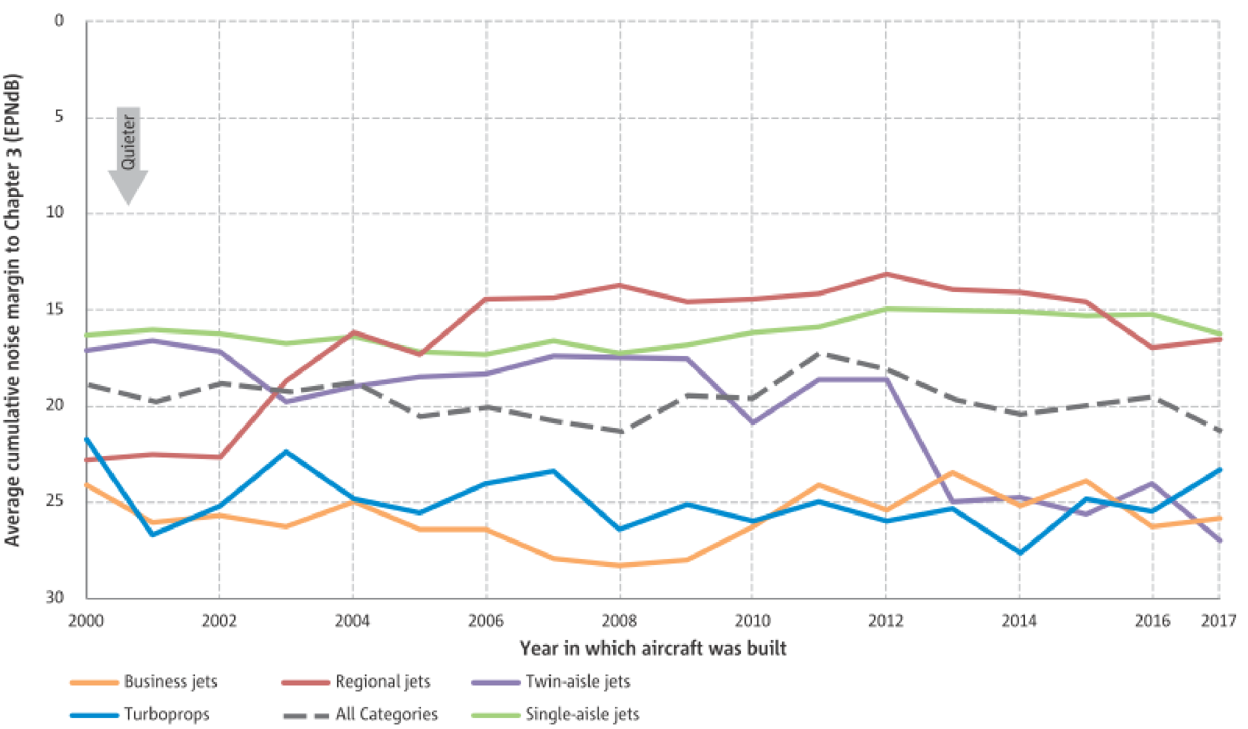


Figure 13.62. Average cumulative noise margin to Section 13.2.1 "Scope" for aircraft built in a given year and registered in EU28+EFTA after 2000.

13.2.6.10 Manufacturer Subsidies

Plane manufacturers have been benefiting from governmental subsidies since the beginning due to the economic importance of the aircraft market and the high development costs that it involves. Regarding competence, subsidies effect in terms of reducing development costs, and so it affects pricing, which impacts on rival performance. The World Trade Organization set up some rules for the commercial aviation market back in 1992. This agreement states the following:

- On the one hand, it puts a ceiling on the amount of direct government support (33% of the total development costs) for new aircraft programmes. It establishes that such support (granted in the form of launch investments, which are repayable royalty-based loans) will be repaid at an interest rate no less than the government cost of borrowing and within no more than 17 years. Basically, this discipline applies to the form of government support mainly in use in Europe.
- On the other hand, the agreement establishes that indirect support (e.g. benefits provided for aeronautical applications of NASA or military programmes) should be limited to 3% of the nation's LCA industry turnover. This discipline is primarily targeted at the support system in use in the US. In contrast to the European system of repayable launch investment, there is no requirement for indirect support to be reimbursed and the generous ceiling of 3% is calculated on the larger basis of the turnover of the LCA industry and applies per individual year.

Both Airbus and Boeing have accused each other several times of using illegal subsidies for their developing programs in both direct and indirect forms. In 2017, Boeing claimed Airbus $21 billion in illegal subsidies in form of launch aids for its programs A300, A340, A380 and A350. On the other hand, Airbus claims that illegal subsidies provided to Boeing have caused the loss of 300 aircraft sales valued in $15-20 billion.

13.2.6.11 China market evolution.

China is one of the most rapidly growing economies in the world, with an expected GDP growth of 4.8% per year. Chinese GDP is estimated to represent the 19% percent of the global GDP by 2037 (according to Boeing Commercial Outlook). This economical growing will also have effects in the aviation market. Today, Chinese airlines account for 14 percent of the global traffic, and the perspectives on the future are growing to over 20% of the global traffic in 2037.

Today, china's aircraft fleet represents 15% of the global fleet, with more than 3500 aircraft on service. Boeing forecasts this number to grow and reach 8600 aircraft on service by 2037, representing 18% share of the world's fleet. Boeing has also forecast a decrement of the single-aisle fleet: In 2017, 79 percent of the aircraft on service in China were narrow-body aircraft, whereas in 2037 single-aisle models will represent around 71 percent. According to this forecast, bigger wide-body aircraft, due to the higher demand and/or limited capacity, will operate several routes now operated by single-aisle aircraft.

China is undoubtedly an important target for plane manufacturers, due to the high economic potential that it has, with a market value of more than $1100 billion. Historically, air fleet of Chinese airlines has been mostly composed by Boeing aircraft. Nevertheless, last data from August 2018 showed Airbus dominancy in the rapidly growing Chinese market. Despite all of this, the country is showing off a lot of effort to develop its own aerospace industry. The Chinese manufacturer COMAC aims to manufacture the first Chinese single-aisle jet to compete with B737 and A320 western models.

The Chinese market is very singular since every contract signed by an airline with an airplane manufacturer has to be previously approved by the Civil Aviation Administration of China (CAAC). This put serious limits on the free trade of jets in the country. For example, if China decided to favour orders to either supplier, as a form of legislation against the U.S. or Europe, that could remove around 25% of single-aisle sales from the other manufacturer.

13.2.6.12 Low-cost operation in the Middle of the Market

Airline business models evolve over time to meet the needs of customers, to take advantage of the opportunity and to respond to their competition. There is no doubt that whilst not new, the low-cost model has helped to deliver additional growth, through the provision of low fares and new city pairs largely, but not exclusively, to the leisure market. Businesses are also benefiting from the new routings and additional connectivity that the model delivers. In recent years, the low-cost model itself has evolved with ultra-low-cost and mid-haul low-cost variants growing the number of seats they offer.

Low-cost business models would not have flourished without the relaxation of government-regulated airline ticket pricing and the removal of regulatory barriers to new market entrants. Recent strong growth of low-cost carriers (LCCs) in the ASEAN area of Southeast Asia illustrates the high impact of the market liberalization. New entrants in this market have reduced airfares and added vast numbers of new routes particularly within the region. The expectation is that the trend toward more liberal air travel markets continues, as consumers have come to expect increased choice and lower prices for airline travel. It is certainly crucial for the continued health of air travel that such liberalization continues around the world.

Asia/Pacific region leads the low-cost long-haul expansion, offering around 40% of the share of seats offered in 2017, in low-cost operations above 2500 nm. The number of seats has been growing exponentially during the last decade, as shown in Figure 13.63. Mid-haul low-cost connections between Europe and North America appeared in 2013 by LCCs such as Level or Norwegian and have been rapidly growing during the last 4 years till reaching 30% of the volume of seats. Another important passenger flow covered by LCCs is Asia/Pacific-Middle East, which represented 11% of the total number of seats offered.

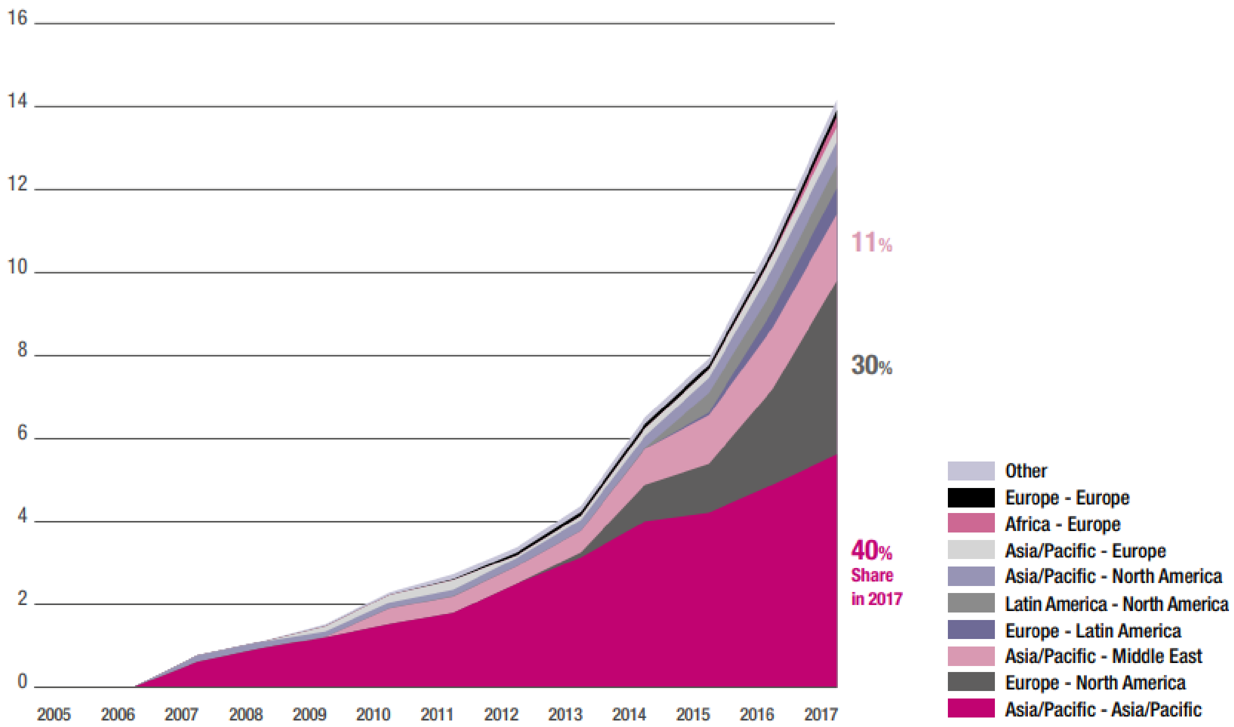


Figure 13.63. Low-cost Carriers seats offered in operations above 2500 nm (Millions).[27]

The number of connections made by LCCs is continuously increasing, especially due to the extended use of secondary airports as airline HUBs, due to the lower fares. In the Middle of the Market (i.e. for mid-haul flights), the number of routes offered by the LCCs is around 11% of the total market. Figure 13.64 shows the number of mid-haul connections made by LCCs in 2018. Europe and North America are the regions more connected by this type of carriers, followed by Asia-Pacific countries. Also, Europe and Latin America are starting to be connected by LCCs as the liberalization of the Spanish-Latin American air travel begins. The airlines considered for this analysis can be found at [66], and the routes from the OpenFlights.org [22] database.

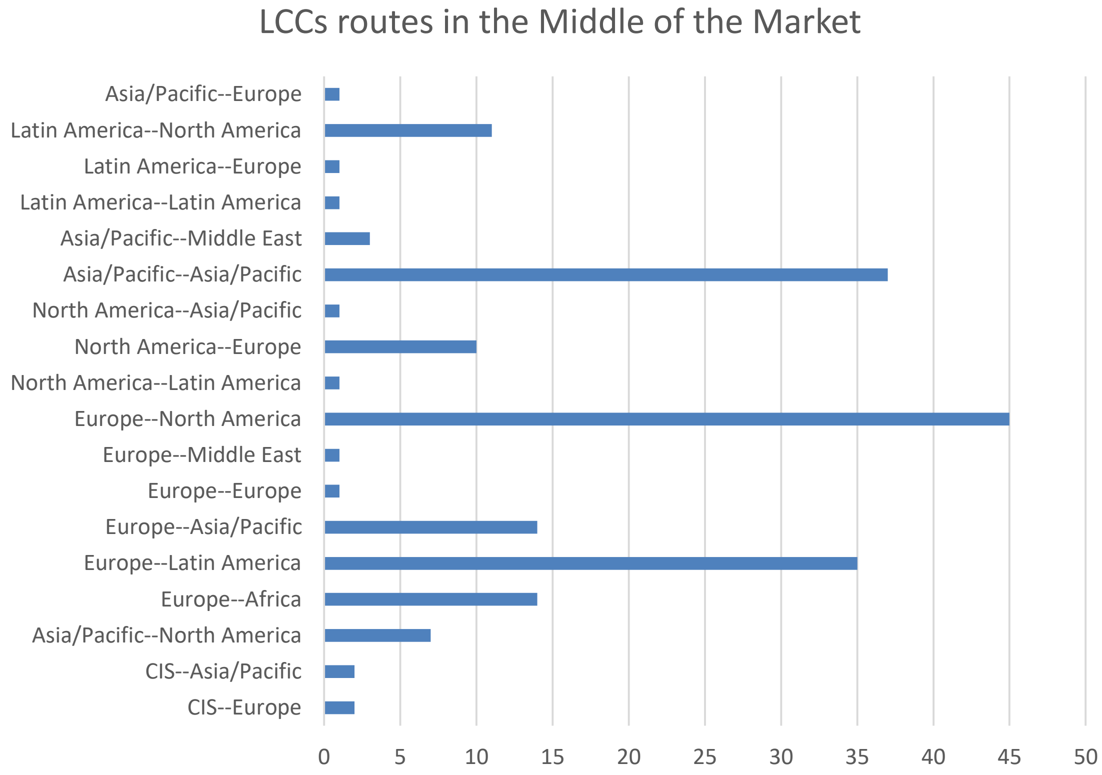


Figure 13.64. Low-cost Carriers number of routes in the Middle of the Market

Considering the totality of operations, the share of LCCs against traditional carriers rounded 30% in 2017 [67] just in Europe, whereas for 2019 has increased to 42% and even 62% for Southeast Asia. Other regions, like Russia and Central Asia, have not developed this business model like in the rest of the world, with only 5% of LCCs operations [68]. The global average in 2018 for short-haul operations (<3000 nm) was 33%. The big presence of LCCs in short-haul flights is mainly due to the regional liberalization of the market between neighbouring countries. While this tendency spreads worldwide, the share of the LCCs in the Middle of the Market is also expected to reach around 30-35% in the following years.

13.2.6.13 Increase in airport congestion

After nine straight years of above-trend passenger growth, many airports are experiencing pressure on operational capacity. This is particularly acute in high-growth regions such as Southeast Asia, China, India and in Western airports where airport expansion is artificially restricted, such as in many parts of Europe.

Adding airports is the most direct means of increasing capacity in the system. Between 2012 and 2018, the world added a net of 176 airports. Most of these (165) were in the Asia-Pacific region. While many airports were newly built, some recommenced commercial service or were converted from military use. Growth through improving existing facilities is more prevalent in well-established aviation markets, with most of the new airports being built in emerging markets. The Asia-Pacific region leads this investment boom with 17 new airports and 17 additional runways planned to open by 2030. Secondary airport growth has also been strong in many regions, absorbing passenger growth from a nearby primary, or hub, airport. Low-cost carriers have grown rapidly at secondary airports because here they avoid the expense, delays and congestion of many primary airports.

In 2018, PARE examined European airport network efficiency through analysing operations and measures that have been taken in the past and to be taken in the following years to improve capacity. In the 2018 YR1 report PARE concluded that major airports are already congested, and traffic flows are harder and harder to cope with. In 2010, five major European airport hubs were at saturation, that is, operating at full capacity: Düsseldorf, Frankfurt, London Gatwick, London Heathrow, and Milan Linate [69]. Key findings in this study were summarized as in [70]:

- Over a European network of more than 2100 airports, 528 airports account for just 25% of airports, but 98% of the departures. Also, the 25 largest airports in Europe generate 44% of all flights and 90% of all traffic comes from the largest 250 airports;
- There is a geographical concentration of airports in the region London-Amsterdam- Munich-Milan, which creates dense air traffic, with large numbers of climbing and descending aircraft, a significant challenge for the terminal area and en-route capacity;
- The cities closest to Europe’s busiest airports have between 4 and 46 airfields within 100 kilometres (km) from the city centre. For 8 of the 10 cities close to Europe’s biggest airports, a single airport handles 80% or more of all the departures within 100 km;
- By 2030, it is expected that no fewer than 19 airports will be operating at full capacity eight hours a day, every day of the year, which means they will be highly congested and 50% of all flights will be affected by delays upon departure or arrival or both.

During the past years, it has been identified a growing gap between capacity and demand at a number of busy European Union (EU) hubs, being predictable that Europe will not be in a position to meet a large part of the expected demand due to a shortage of airport capacity. In concrete terms, in 2050, it is estimated that 36% of flight demand will not be accommodated at European airports. Table 13.13 shows the airport congestion forecast for 2025 and the capacity assumptions back in 2010.

Airport	2010	2017	2025	Capacity assumptions
Amsterdam Schiphol	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Assumes annual movement cap raised to 510,000 in November 2010 but no further increase
Dublin	Sufficient capacity most or all day	Sufficient capacity most or all day	Sufficient capacity most or all day	Second runway built when needed
Düsseldorf	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Assumed 10% increase in capacity in 2015 but no further increase
Frankfurt	Demand exceeds capacity most or all day	Sufficient capacity most or all day	Demand exceeds capacity during part of day	New runway (2011) and terminal (2015) allow increases from 83 to 126 movements/hour
London Gatwick	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Assumes no new runway but increase of 2-3 movements/hour on current runway
London Heathrow	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Assumes no third runway, or mixed mode, or relaxation of annual movement cap.
Madrid Barajas	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Assumes ATC improvements increase capacity from 98 to 120 movements/hour by 2020 (increase phased in from 2014)
Milan Linate	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Assumes no amendment to Bersani Decree
Munich	Demand exceeds capacity during part of day	Sufficient capacity most or all day	Demand exceeds capacity during part of day	Assume third runway operational by 2017
Palma de Mallorca	Sufficient capacity most or all day	Sufficient capacity most or all day	Sufficient capacity most or all day	Assume additional capacity added when required
Paris CDG	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Demand exceeds capacity most or all day	Assumes increase from 114 to 120 movements/hour by 2015, but no further increase (e.g. fifth runway)
Paris Orly	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Demand exceeds capacity most or all day	Assumes no relaxation of annual slot cap
Rome Fiumicino	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Assume improved ATC allowing 100 movements/hour but no new runway
Vienna	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Demand exceeds capacity during part of day	Assume third runway operational in 2020, initially allowing 80 movements/hour increasing to 90 movements/hour by 2025

Table 13.12. EU's airport congestion forecast.

In 2009, Givoni and Rietveld [71] explored the implications of the choice of aircraft's size by airlines into airport congestion, analysing more than 500 routes in the EU, US and Asia and providing evidences that the choice of aircraft is mainly motivated by route characteristics (e.g. distance, level of demand and level of competition) and almost not at all by airports' characteristics (e.g. number of runways or level of congestion).

Airlines' choice of aircraft size has a direct effect on congestion at airports that operate close to capacity. At Chicago, O'Hare congestion prevails during long periods of the day. In 2004, the cost of congestion imposed on a United Airline's flight departing at 15:00, when there were 28 aircraft queuing for take-off, was estimated at $10,035 and on a flight departing at 18:00, when there were 27 aircraft queuing for take-off, at $5,165 [72]. At the current situation, "even a relatively small change in the number of flights has the effect of reducing delays considerably"

Offering less frequency and bigger aircraft on some flights would help to reduce congestion in airports that have reached their maximum levels of capacity. The Average number of seats offered by airlines in 2018 was 191. The Airline Monitor [73] forecasts this number to grow up to 220 by 2040. In this case study, a scenario where the airport congestion prevails will be examined. In this situation, airlines will be forced to use bigger aircraft and offer less frequency on some routes. This scenario is described in Section 13.2.13.

13.2.7 Forecast for MoM sector

There is a lot of information and different points of view when it comes to commercial aircraft market forecast. This industry is growing geometrically every year so that its analysis becomes more and more difficult due to the different factors influencing the trends and the changing nature of its dynamics. Many companies and authors divide and explore different sublayers of the market, such as Bombardier in [74], where focuses on the regional jet market. Other authors divide the market according to aircraft seat capacities, like Airbus [27] or Boeing [28]. Nevertheless, there is no published forecast related to the Middle of the Market. This segment of the market, of which borders are uncertain for many analysts, holds more than 20% of the delivered aircraft.

The main objective of this chapter is to obtain a detailed Middle of the Market forecast based upon the information analysed in 05 about different market forecasts together with additionally open-source data of routes and types of planes used as a baseline. This market MoM will be useful to better understand the trends of this particular segment and quantify its size and value.

13.2.7.1 Forecast methodology

In this section, the methodology used for forecasting the MoM aircraft market is presented. First, the baseline forecast, and the ranges established for the calculations will be discussed, comparing the results of the general market forecasts showed in 0. After it, the source of data and the way of treating the information will be discussed.

Baseline forecast and forecasts ranges.

The five market forecasts presented above give a big amount of information regarding aircraft deliveries expectations and fleet renovations. Each one of the authors has used their own hypotheses and data from different sources, which leads to significant differences in the results. Moreover, segmentation of the market differs one from another, especially when it comes to manufacturers, as presented in previous sections. Discrepancies between market forecast have been discussed in the previous section, providing a qualitative comparison of the hypotheses and results. Despite all those differences, the forecasts presented represent a strong data set and give solid information about the market and prognosis over time. PARE will integrate the information of these market forecasts in order to provide the most possibly detailed data about the Middle of the Market sector, establishing a set of conclusions out of it.

The five market forecasts analysed predict air traffic to grow in the period of 2017-2037 with an expected yearly rate in the range of 4.5% to 5.1%. The most "optimistic" numbers are the ones from the Airline Monitor report, which expects the worldwide passenger turnover (RPK) to triplicate over the forecast period, with an average yearly growth of 5.1%. On the other hand, the most "pessimistic" ones belong to Airbus' report, as well as the Japanese JADC. In the middle of this range, there is Boeing's approach, which estimates a rate of 4.7% yearly growth, alongside the Russian UAC, with an estimation of 4.6% per year.

PARE's Middle of the Market forecast will be structured around Boeing's traffic prognosis values, using the results of the open dataset released by the company as a baseline for the calculations. In addition to this, two alternative scenarios will be analysed: First, an "optimistic" approach based on the highest numbers on air traffic growth according to the results presented in the Airline Monitor report, and secondly, a "pessimistic" approach using the lowest numbers of the forecast, i.e., a growth of 4.5% per annum. This will provide a range of acceptable values based on the experience of the companies that performed the previous forecasts. Thus, the results will be more consistent and contrastable.

Data sources and steps

The data of the previous general market forecasts presented will be used to predict the MoM sector size and growth perspectives. Figure 13.65 shows a summarized scheme of the methodology. As shown in the picture, for the baseline forecast, this consists of two main steps: the traffic forecast and the fleet forecast. Each step groups data from different sources and different calculations as stated hereafter:

1. **MoM traffic forecast:** the MoM traffic size is calculated based on the data provided by the Boeing Global Market Forecast [28] dataset and the RPKs distribution by distance and region provided by the UACs market forecast report [30]. Using this data and the annual growth by region percentage estimated by Boeing (for the baseline forecast) the MoM traffic demand is projected over the period 2018-2040.

2. **MoM fleet forecast:** using the traffic prognosis calculated in the previous step, the fleet size is estimated using airline performance data provided by the Airline Monitor market forecast report [73]. The fleet is calculated yearly over the projected air traffic demand. An insight over the calculations in this step is provided in the Annexes. Additionally, the retirements of the MoM sector are estimated using the Airline Monitor retirements forecast, which details forecast retirements by model for the period 2018-2050. Integrating this information with the estimated Middle of the Market share of each model presented in 0, it yields the retirements forecast by model for the MoM sector specifically. The total fleet in 2040 will be composed of those aircraft that stay in service from nowadays' fleet, and new deliveries. Equally, new

deliveries will be destined to either replace older aircraft from the actual fleet or to expand the fleet.

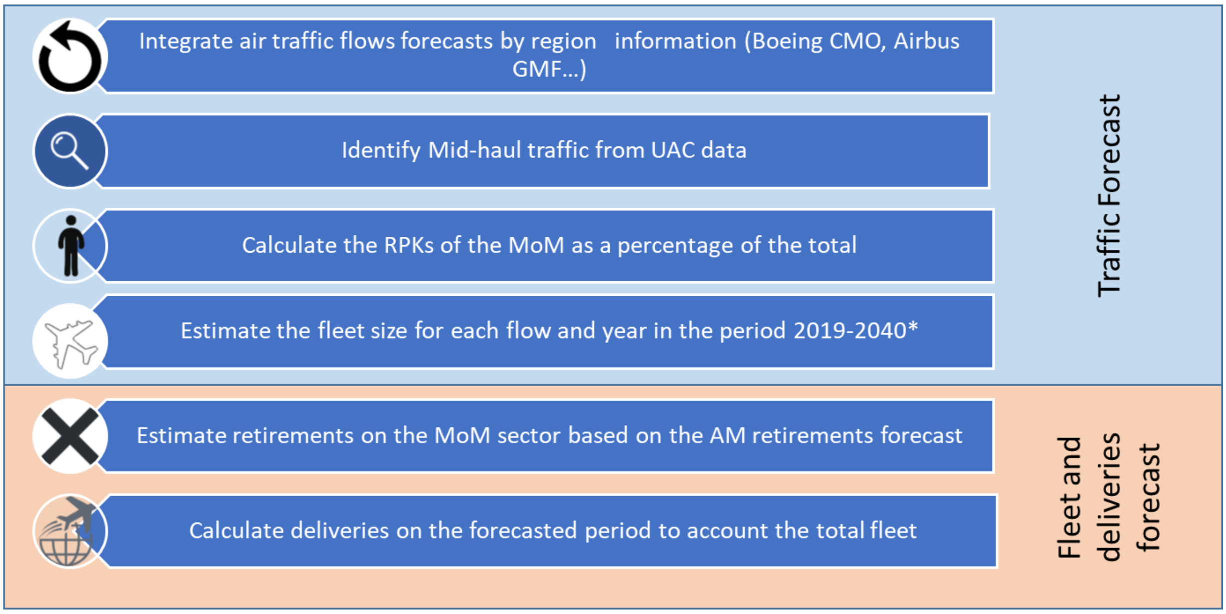


Figure 13.65. MoM forecast methodology

13.2.7.2 MoM sector forecast results

Following the methodology presented in the previous section, the following results have been extracted. First, the RPK distribution by distance is extracted from the UACs report and the traffic forecast results are shown. After it, the results of the fleet forecast are presented both by region and globally, and the evolution over the forecast period. Finally, the retirements and resultant deliveries forecast results are discussed.

Passenger turnover distribution by distance

The passenger distribution by distance is calculated by UAC in [30]. Figure 13.66 shows the differences between regions regarding flight distance tendencies. Regions like China, South America and the former Soviet Union (CIS), predominantly travelled shorter distances in 2017, whereas in other regions, like the Middle East, the majority of the air traffic was concentrated in medium- (46%) and long-haul (22%) flights. In Europe and North America, the distribution is closer to the world's average, which was 62% for short-haul, 21% for medium-haul, and 15% for long-haul traffic.

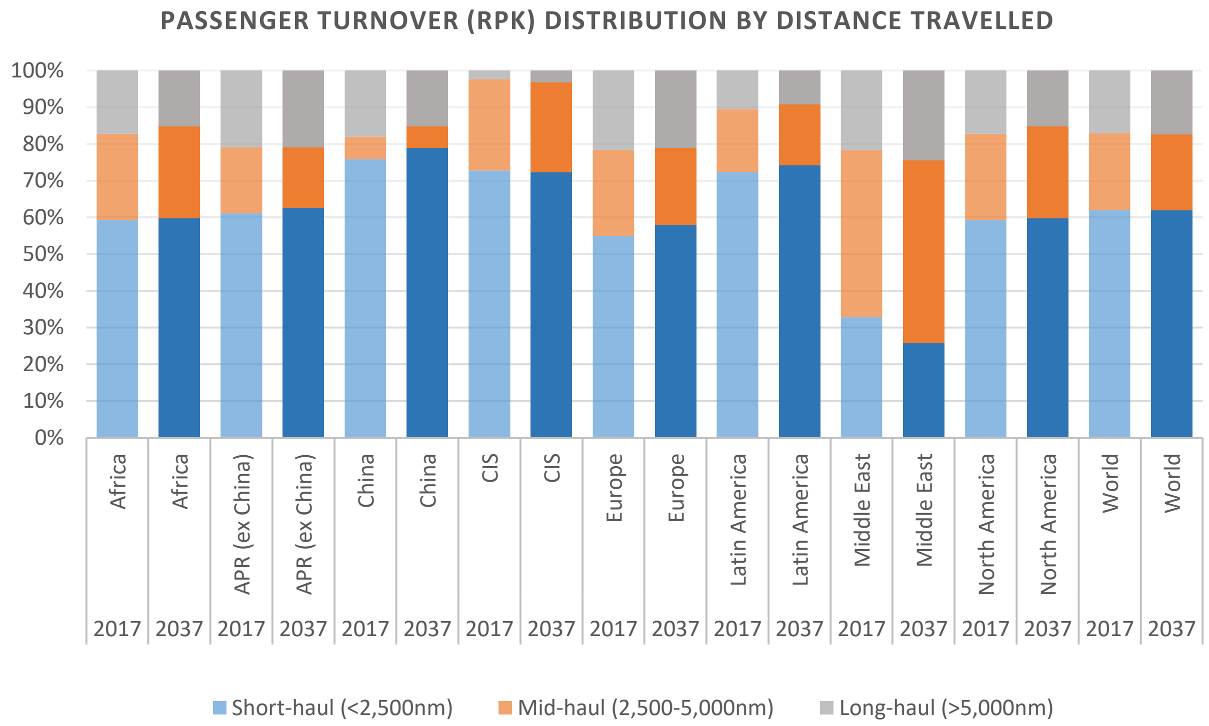


Figure 13.66. Passenger turnover distribution by distance travelled and region in 2017 and 2037 forecast. [30]

UAC's 2037 forecast predicts this distribution to change regionally, for example by an increment of the short-haul traffic in China, or an increment of the medium- and long-haul flights in the Middle East. Nevertheless, there is no change forecast in the overall worldwide distance distribution.

'Middle of the Market' traffic forecast

The analysis below showed that the Middle of the Market (or medium haul) traffic 21% of the total passenger revenue (RPKs) worldwide. The following section will present the traffic forecast of this segment by region, considering the total distribution presented above. The MoM traffic forecast results by region are summarized in Table 13.13

Region	Average Growth p.a.	Traffic 2018 [RPK]	Fraction of Mid-haul traffic	MoM Traffic 2018 [RPK]	MoM Traffic 2040 [RPK]
Asia-Pacific	5.6%	2628.1	12.8%	365.1	1107.9
North America	2.6%	1784.5	23.5%	431.6	812.4
Middle East	5.9%	748.3	45.5%	362.2	1407.9
Europe	3.5%	2244.0	23.5%	542.9	1021.3
Latin America	5.4%	413.2	17.2%	74.8	228.7
Africa	4.6%	168.7	23.5%	41.6	119.7
CIS	3.5%	257.0	24.9%	66.1	138.6
World	**4.5%**	**7986.8**	**22.6%**	**1884.4**	**4836.5**

Table 13.13. MoM traffic forecast values

The following figure shows the traffic forecast in terms of passenger revenue (RPK) by region.

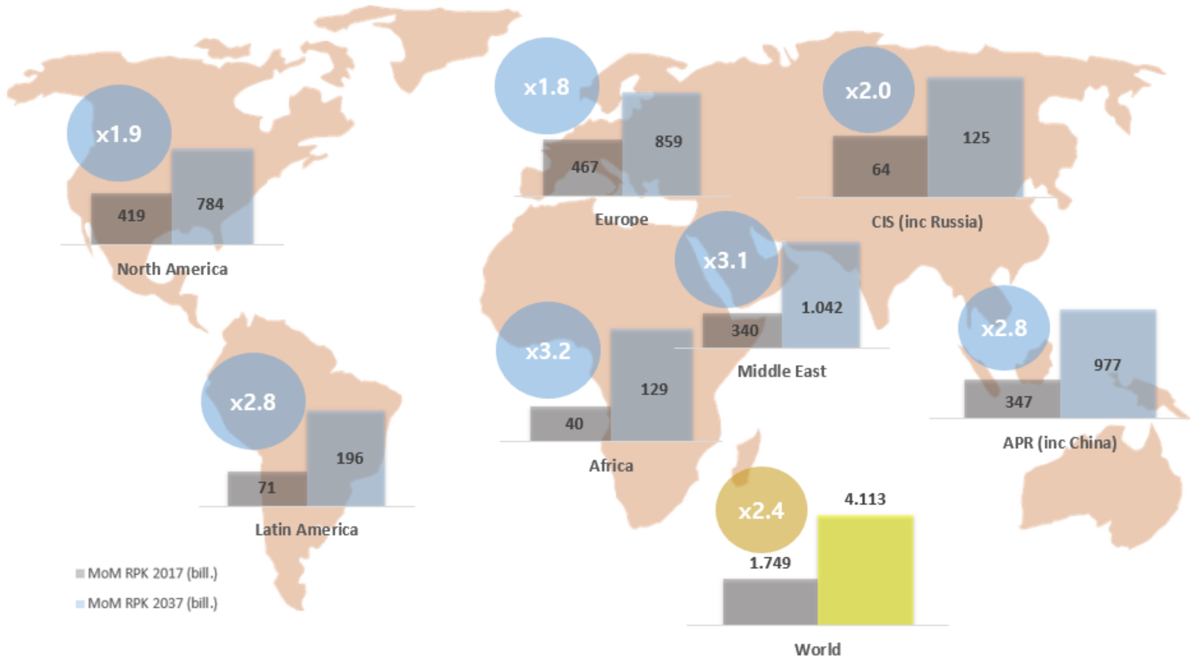


Figure 13.67. Middle of the Market traffic forecast

Most of the mid-haul traffic is concentrated on the flows Middle East-Europe, EEUU-Europe and Middle East-Northeast Asia, mainly due to business reasons. Figure 13.67 shows that the traffic in the medium-haul segment will be incremented by a factor of 2,4 worldwide, with more importance in some regions like the Middle East, where it will triplicate its demand or the area of Asia-Pacific region. In general, mid-haul traffic will grow at a slower rate than the general traffic, since the regions holding the majority of the worldwide passenger revenue are those where the traffic is concentrated mostly on short-haul flights. Moreover, the traffic forecast is based on UAC's data of passenger revenue by the segment of the flight, which predicts the Middle of the Market traffic to slightly decrease by 0.3% in 2037.

Fleet forecast

The traffic forecast presented in the previous section shows that the Middle of the Market represents about a 21% of the total air traffic in the world, and UAC estimates that it will maintain its contribution over the next 20 years. In every region, the evolution will be different, as estimated in the analysed market forecasts of the previous section. In this section, the Middle of the Market fleet forecast will be presented, focusing on the division of the market by regions and estimating aircraft retirements and deliveries in the segment over the period 2018-2040.

The forecast uses a methodology focused on the capacity of the sector needed to satisfy a determined air traffic demand. With the air traffic volumes forecast in the previous section, the required fleet to serve this demand is calculated based on a standard aircraft seat configuration, as well as several aircraft performance indicators (such as utilization time or block speed). For an insight over the details in this calculation see the Annexes located at the end of the document.

The standard aircraft seat-configuration assumed for this analysis has been determined from the analysis of route trends in the Middle of the Market regionally, and it varies significantly between regions.

Region	Average seats	Av. Load Factor	Utilization (h/day)	Block speed (km/h)
APR (inc. China)	277	82%	8.9	594
North America	267	84%	8.5	665
Middle East	295	78%	9.9	695
Europe	276	84%	9.8	623
Latin America	249	82%	8.9	594
Africa	272	71%	5.5	637
CIS (inc. Russia)	216	81%	8.8	623
World	273	80%	8.9	666

Table 13.14 shows the average capacity offered by each region for routes on the mid-haul segment during the year 2018. There are significant differences between regions of the world, with Asian and Middle Eastern airlines offering higher capacity for MoM routes than in the rest of the world. This is a reason why the market is differently weighted in each region.

Region	Average seats	Av. Load Factor	Utilization (h/day)	Block speed (km/h)
APR (inc. China)	277	82%	8.9	594
North America	267	84%	8.5	665
Middle East	295	78%	9.9	695
Europe	276	84%	9.8	623
Latin America	249	82%	8.9	594
Africa	272	71%	5.5	637
CIS (inc. Russia)	216	81%	8.8	623
World	273	80%	8.9	666

Table 13.14. Average capacity offered in mid-haul routes. Data

Using this standard configuration and the air traffic volume data from the previous section, the estimated fleet for the forecast period was calculated. Geometric growth of the 4.7% [28] per year on the traffic has been assumed, which results in a growth of 4.2% annually on the global MoM fleet. Additionally, airline performance parameters have been assumed to improve over time. These indicators are an important factor when calculating the fleet based on the traffic volumes, meaning that a higher airline performance will result in smaller fleet growth. These parameters' values in 2018 are shown in

Region	Average seats	Av. Load Factor	Utilization (h/day)	Block speed (km/h)
APR (inc. China)	277	82%	8.9	594
North America	267	84%	8.5	665
Middle East	295	78%	9.9	695
Europe	276	84%	9.8	623
Latin America	249	82%	8.9	594
Africa	272	71%	5.5	637
CIS (inc. Russia)	216	81%	8.8	623

World	273	80%	8.9	666

Table 13.14, and their improvement over time is as follows:

- **Average load factor,** which in 2018 had been 82%, and has been assumed to grow at 0.5% annually.
- **Aircraft utilization** was, on average, of 8.9 hours per day in 2018, being higher in regions like Europe (9.8) or Middle East (9.9), and it is assumed to grow till 9.1 hours per day by 2040.
- **Block speed** was 656.1 km/h on average in 2018, and it is assumed to reach 666.1 km/h by 2040.

At the same time that the fleet is growing due to the demand for more aircraft to cover the demand, the actual fleet gets older and eventually needs to be replaced. Thus, some of the newly delivered aircraft will be accountable to replace the older fleet, whereas some of these aircraft will remain active.

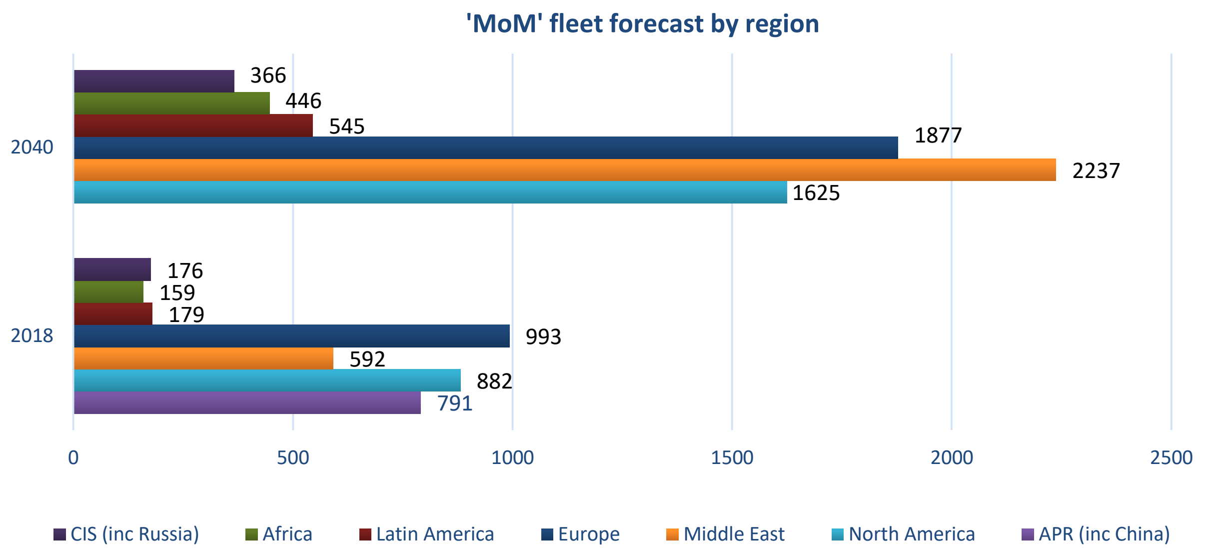


Figure 13.68. MoM fleet forecast by region

Region	MoM fleet 2018	MoM fleet 2040 (growth)	MoM Retirements	MoM Deliveries (% of total)
Asia-Pacific	791	2401 (x3.0)	612	2257 (27%)
North America	882	1625 (x1.8)	520	1286 (15%)
Middle East	592	2237 (x3.8)	528	2205 (26%)
Europe	993	1877 (x1.9)	588	1497 (18%)
Latin America	179	545 (x3.0)	139	513 (6%)
Africa	159	446 (x2.8)	119	413 (5%)
CIS	176	366 (x2.1)	110	305 (3%)
World	**3772**	**9497**	**2615**	**8476**

	(x2.5)

Table 13.15. Fleet, retirements and deliveries by region

Forecast values show that global MoM fleet will be 2.5 times bigger in 2040 than what it was in 2018. Some regions will experience a bigger growth in terms of the fleet within this market, which can be translated into Middle of the Market main business focuses. Asian airlines (which include those from Middle-East and Asia-Pacific regions) will account around the 50% of the total mid-haul fleet, whereas Europe and North America will decrease their share of the total fleet from the 50% in 2018 to 37% in 2040, as a result of the accelerated growth from the emerging countries. These results are illustrated in Figure 13.68.

More than 2500 aircraft belonging to the MoM sector will be retired worldwide, and the global market will account more than 8400 deliveries in the forecast period. The results of the forecast are presented in Figure 13.69, differentiated by region. The Asia-Pacific region together with the Middle East will account more than 60% of the deliveries within this market, whereas Europe and North America will receive a third of the total new-built aircraft. A total of 588 aircraft will be retired in Europe within the MoM and 520 in North America, which means 59% of the 2018 fleet, will have to be replaced in both cases. Asia-Pacific and the Middle East have different tendencies, with most of the deliveries accounting to the growth of the fleet, but also they will experience a big renovation of the fleet. Nearly 80% of the 2018 MoM fleet will be replaced by 2040 in Asia-Pacific, and about 90% in the Middle East. 73% and 76% of the deliveries will expand the fleet of the Asia-Pacific and Middle Eastern airlines, respectively. In Europe and North America, these fractions are of 60% and 57% respectively. A summary of the retained, replaced and new aircraft is illustrated in Figure 13.69.

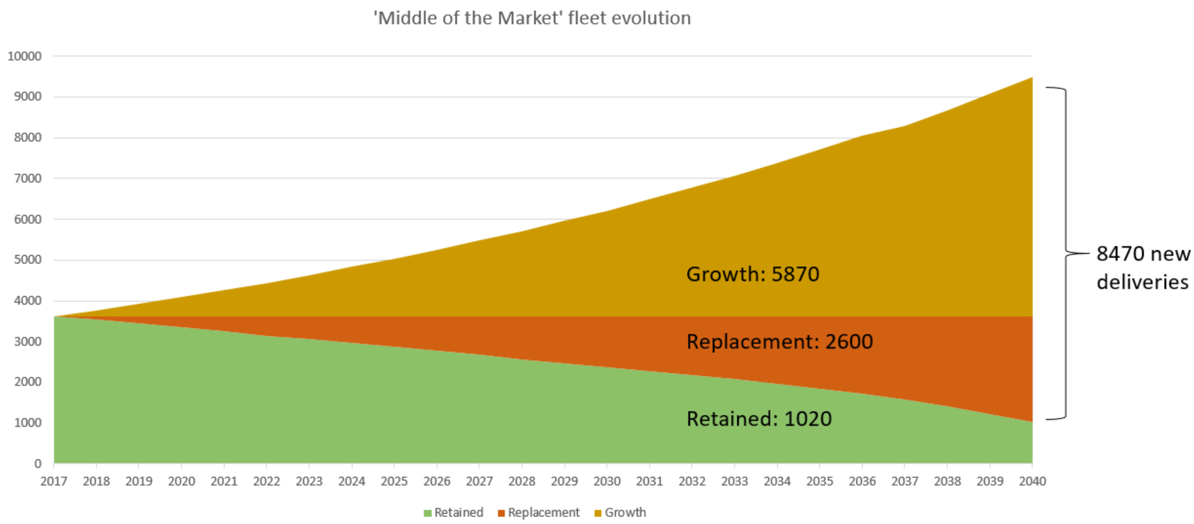


Figure 13.69. Middle of the Market fleet evolution.

The results of the MoM forecast here presented can be contrasted and verified with the aircraft market forecasts from different authors that include the totality of the aircraft market and were exposed in 0. The forecasts made by Boeing or Airbus can be taken as reference for the comparison. For example, Boeing estimated around 42,000 deliveries in the period 2018-2037 in all segments. The value of 8470 MoM deliveries of this forecast represents 20% of the 42,000 aircraft forecast by Boeing. This value can be considered as reasonable since the mid-haul traffic represents about 25% of the global air traffic, according to 0.

Forecast ranges

The MoM forecast determines the evolution over the time of the mid-haul traffic and the estimated fleet that will compose this segment over the period 2018-2040. The values previously presented are based on the air traffic growth forecast by Boeing in [28], and constitute the baseline forecast. Other air traffic forecasts were analysed in the previous section, providing a range of acceptable values from either a more pessimistic or optimistic point of view regarding air traffic growth. Thus, in [73] the Airline Monitor, more optimistically, forecasts annual growth of 5.1%, whereas Airbus is more conservative in [27] and forecasts a 4.5% annual growth. The Middle of the Market traffic growth, fleet and deliveries were calculated using the different approaches, as shown in Table 13.16.

Values	Low demand	Baseline	High demand
MoM Traffic 2040 [bill. RPK]	4836.5	5067.5	5302.2
MoM Fleet [units]	8945	9497	9907.8
Deliveries [units]	8091	8655	9073

Table 13.16. Forecast ranges

The variation over the baseline forecast is shown in Figure 13.70, rounding values of 6% for deliveries and 5% for the fleet forecast respect to the baseline scenario. Replacements have been assumed unaffected by the different scenarios since the dynamics of fleet renovations remains the same independently of how the air traffic evolves. A more precise approach would be to consider certain resilience of the fleet retirements to the demand since airlines are more eager to expand the life of an aircraft due to the lower demand.

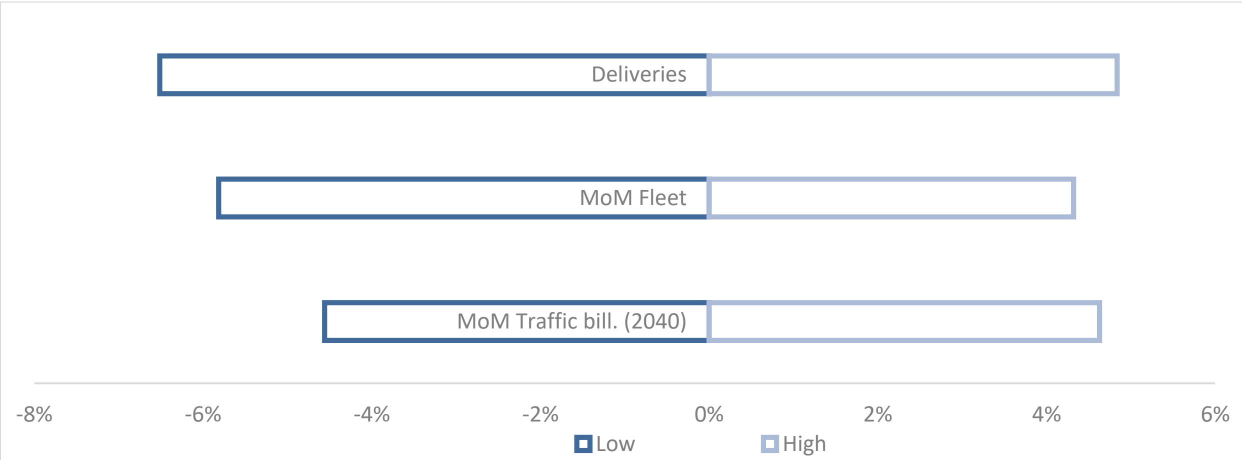


Figure 13.70. Forecast range of variation.

13.2.8 Airplane Program Costs and Project Valuations

In this chapter, an aircraft program cost model is developed in order to estimate the payoffs for the manufacturer's strategies under different scenarios and varying market conditions. These payoffs will be the outcome of the games that will allow determining the best manufacturers' strategies to be applied under different scenarios proposed in the study.

However, it is important to note that there will be uncertainty in the model's input parameters since companies' financial data are not public in order to protect competitive interests. For that reason, the purpose of this study is to determine the rank ordering of manufacturers' strategy payoffs with the aim of using them in game theory analysis.

The payoffs will be calculated taking into account the aircraft total life-cycle cost (LCC), which include typically four phases: design development, production, operation and retirement. Figure 13.71 shows the different life cycle costs of a product, indicating that most of the costs are incurred in the operational phase, and this is even more significant in the case of aircraft, which have very long-life spans. For this reason, airlines decisions of purchasing an aircraft are very influenced by operating costs, which makes manufacturers search efficient and profitable ways to reduce these costs since it could allow them to gain significant market share.

The figure also shows that it is on the early phases of the product design that most of the LCC are defined (at the end of the design process, around 80% of the costs are already defined, regardless of almost everything that comes afterwards). This shows how important it is to design the right aircraft since very little margin exists for the airline to reduce its operational costs.

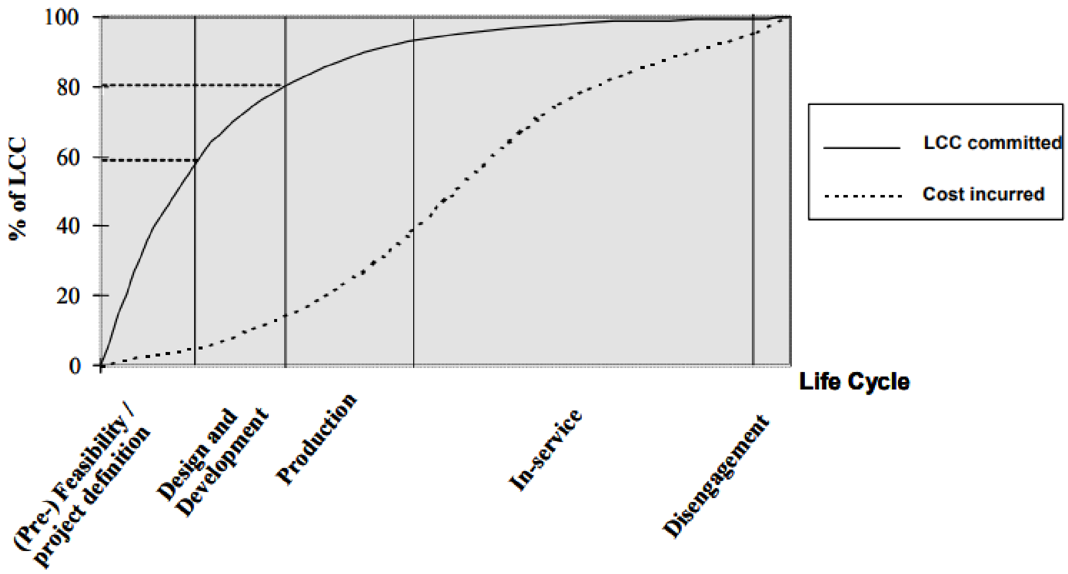


Figure 13.71. Evolution of Life Cycle Costs (committed and incurred). Source: Task Group SAS-054, Methods and Models for Life Cycle Costing.

The model proposed in the study will estimate the costs of the following phases of the aircraft life cycle: development, production and operation for the study period, which is framed between 2020-2040. Figure 13.72 shows the methodology followed in order to calculate all the costs necessary to develop the model, which comprises several steps. The final aim is to calculate the Net Present Value (NPV), which is the output metric chosen to calculate the payoffs. The NPV metric is based upon the existence and accuracy of a discount rate or factor, which is used to discount all forecast cash flows to reflect the opportunity cost of capital, and NPV is computed as the sum of all the discounted cash flows of a project. While the appropriate discount factor is often difficult to rigorously calculate and confirm, the NPV method is consistent across different projects and provides a good baseline for value measurement.

In order to estimate NPV values for manufacturers, the methodology followed comprises several stages, which are shown in Figure 13.72. Each of these phases will be described in detail in subsequent sections, although in this point it is explained an overview of the process.

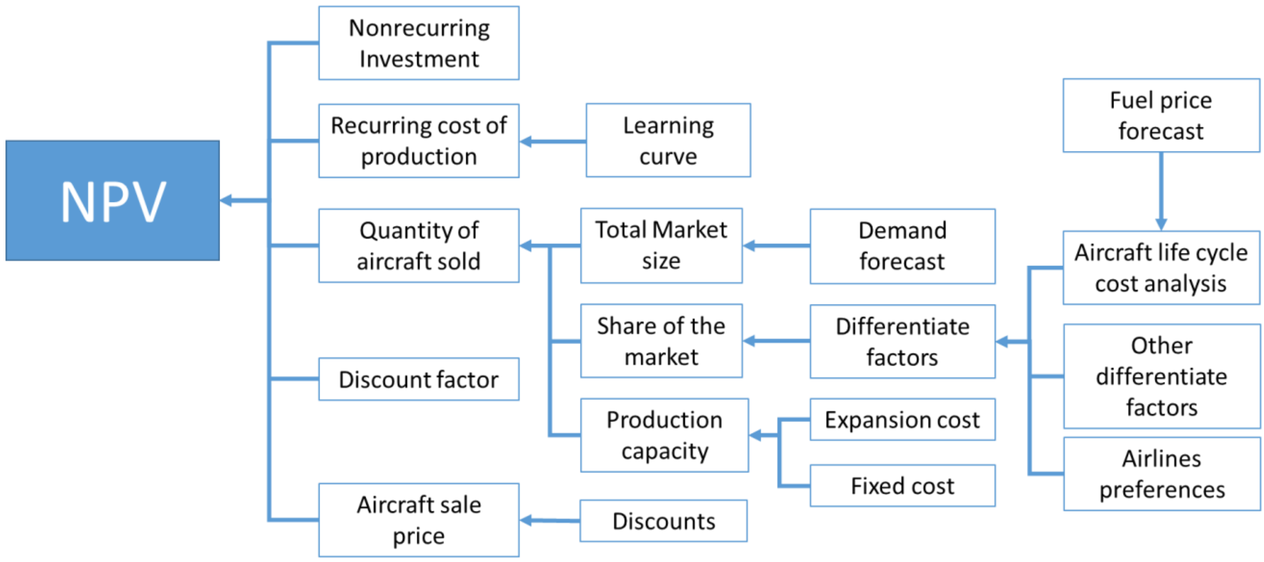


Figure 13.72. Model program cost methodology

In the first place, non-recurring and recurring costs will be calculated, which correspond with development and manufacturing phases, respectively. Nonrecurring investments involve Research, Development, Testing and Evaluation (RDT&E) costs of the aircraft, which will be estimated based on parametric models generally called Cost Estimating Relationships (CERs). The DAPCA IV[75], developed by RAND Corporation, is the model chosen to calculate development costs, by using performance parameters of the aircraft such as the empty weight or maximum speed.

On the other hand, recurring costs of production are assumed to be subject to a learning curve. This process is characterized in aircraft production by a significant decrease in unit cost as additional aircraft are built, eventually reaching a unit cost approximately constant. The learning curve depends on a parameter known as “slope”, which describes the magnitude of the learning curve effect.

Once the recurring and non-recurring costs have been calculated, an essential phase is calculating the operating costs of the aircraft considered in the study for the 2020-2040 period. The estimation of these costs is divided into several items of which cost is necessary to calculate, such as maintenance, crew or fuel. These costs vary considerably depending on the type of aircraft considered, that is, the fuel consumption of wide-bodies is greater than narrow-bodies due to their bigger structure and flight time, which is reflected in the cost, being significantly higher.

For the operation costs calculation, the TU Berlin DOC Method has been chosen, due to its simplicity as it allows to estimate Direct Operating Costs of an aircraft based on data which are public. Indirect Operating Costs (IOC), which forms together with the Direct Operation Costs (DOC) the Total Operating Costs (TOC) of a particular airline or aircraft, are not calculated in this model as they are related to the management strategies and level of service of the airline. Therefore, with this model, it will be only calculated the Direct Operating Costs, which are the most relevant for the study since they are highly dependent on the design of the aircraft. The operation costs obtained for each aircraft will be determinant to obtain the market share based on differentiating factors like fuel efficiency, or payload capacity. Additionally, it will be required to consider airlines preferences to calculate the market share, as some airlines will never choose to switch to competitor's manufacturer although it produces more efficient aircraft, due to fidelity, training and spare parts issues.

The market share model developed together with the demand forecast performed in 0 will allow obtaining the quantity of aircraft that are expected to be sold for the Middle of the Market. It will be also necessary to consider in the calculation the production capacity of manufacturers, which is limited and in which it could be required to invest in case of expecting an increase in the number of units produced by year.

Once all the previous costs have been calculated, it is important to consider the aircraft sale price. Generally, an aircraft is set with the objective of recovering gradually the development investment with every unit sold, so that the money spent on this phase must be divided by a given number of aircraft, according to the manufacturer expected sales. The production costs must then be summed to that value. This will yield the cost of the aircraft, which will finally lead to the aircraft-selling price so that the price established will affect manufacturers' benefits. If this price is very slow, it could lead to a manufacturer's losses while if it is very high it could impact airlines' interest, resulting in a lower number of units sold. For this reason, the acquisition price is a critical factor to be considered that can significantly affect airlines purchasing decisions. The sales price data have been obtained from Airbus and Boeing web pages.

Finally, with all the previous stages calculated, the Net Present Value (NPV) is calculated with the following equation:

$$\pi_{fi} = E_{it}\left[\sum_{t=1}^{n}(\delta_t[p_{it}q_{it}(p) - c_{it}q_{it}(p) - I_{it}] - I_{i0})\right]$$

This equation will provide the payoffs of manufacturers that will be used as outcomes for gaming analysis in 0.

13.2.8.1 Development and production costs

The first phase of the aircraft life cycle, the development costs, refers to the Research, Development, Testing and Evaluation (RDT&E) costs. Generally, this phase includes the technology research, design engineering, development support, prototype fabrication, flight and ground testing and evaluations for operational suitability. It also includes the certification costs of the civil aircraft. RDT&E costs are essentially fixed, denominated as non-recurring costs, which means they are incurred just once and are independent of the number of aircraft produced.

The production costs are, on the other hand, recurring costs, since they are based upon the number of aircraft produced, considering that the cost per aircraft is reduced as more aircraft are produced. That is, the more aircraft produced, the more the manufacturer learns and the cheaper the next aircraft can be produced. This is known as the "learning curve" effect. Aircraft production typically follows a 75-85% learning curve. Due to the learning curve effect, it has no sense to compare between a new aircraft which has just entered production and an old aircraft which has already been produced in hundreds or thousands. Production costs cover the labour and material costs to manufacture the aircraft, including airframe, engines and avionics. It also includes production's tooling costs and quality control costs.

Most of the available development and production cost estimating methods in the literature are based on parametric models. These models are simply mathematical equations which use a few performance parameters of the aircraft that are somewhat related to its costs of development and production to estimate the different cost elements. These relationships, often called Cost Estimating Relationships (CERs), are obtained from statistical analyses, so, in order to provide statistically meaningful results, a substantial amount of data is needed. However, they provide a useful method to estimate the costs of an aircraft program when little detail is known from the aircraft characteristics.

Rand Corporation has published four reports from 1966 to 1987 with parametric methods for estimating aircraft airframe costs for the development and production phases. These reports, known as DAPCA (Development and Procurement Costs of Aircraft) models, were developed for use in planning and evaluation of military aircraft programs by the US Air Force. The DAPCA IV model is the most recent of them. They use CERs for estimating the cost of the whole program and of each of the elements into which they divide the program. The relationships are obtained using cost data gathered from airframe manufacturers and a database consisting of around 30 military aircraft. Since the data is gathered from military programs, the models are more suitable to calculate the cost of military aircraft and not so much for commercial ones. The data is then statistically analysed and exponential regressions are obtained relating a few physical and performance parameters to the costs.

Several authors have used the Rand Corporation models to estimate aircraft costs. On the one hand, Raymer (1992) [76]used the more recent version of the Rand reports, the DAPCA IV, as a base to estimate the development (RDT&E) and production costs. Therefore, it is also based on data collected from military aircraft. The costs elements considered are engineering, tooling, manufacturing and quality control (calculated in hours); and development support, flight-testing and manufacturing material (calculated in dollars). In addition, a list of values for a correction factor for the materials used in the aircraft is presented, since the hours calculated on DAPCA IV were based on aluminium aircraft. Average 1986 wrap rates, which include not only the direct salaries but also employee benefits, overhead and administrative costs, are listed for each of the cost elements. Finally, Raymer suggests multiplying the calculated total costs of the aircraft by an" investment cost factor", to take into account the cost of money and the manufacturer profit.

On the other hand, Corke (2002) [77]presents both the DAPCA II and the DAPCA IV equations. The cost elements used are the same and are divided by the RTD&E (which includes also the flight testing) and production phases. Corke makes the conversion of the costs from the reports' year to the present using the Consumer Price Index (CPI). Hourly rates (which include salaries, overhead, benefits, administrative expenses and other direct charges) are converted for each of the cost elements assuming a linear variation along the years. A 10% profit is assumed for the whole program.

However, one of the most important characteristics of these methods is that they are all very old. This is a problem when thinking of using them for the aircraft developments of today. Several new technologies, materials and production techniques have emerged, and those that were new at the time these methods were developed are now in a much more mature state, which implies that their costs are lower now. Nevertheless, the fact that the Rand methods have been much more recently used in[76] and [77], respectively, indicates that they are at least useful for comparison up to an acceptable degree of accuracy. The second characteristic of these CERs is the fact that they are developed for use in military aircraft, which have different cost characteristics, since the nature of the programs is inherently different (for example, the use of more advanced technology or the higher costs of specific parts that require high-performance characteristics).

In spite of the limitations of the methods previously mentioned, they will be used in this study to calculate development costs, due to its simplicity as well as the possibility of using them without knowing a great detail of aircraft performance characteristics. Corke (2002) is the method chosen as it is the most recent version available, which is based in turn in the DAPCA model.

Besides, the production costs will be calculated considering a learning curve that allows manufacturers to reduce costs as more aircraft are produced. It is used the learning curve modelled by Raymer (1992), considering a slope of 85% which is a value very typically used in the aerospace industry [78].

New aircraft development non-recurring costs

Non-recurring costs refer to the Research, Development, Testing and Evaluation (RDT&E) costs. This includes the technology research, development, engineering, fabrication and flight testing of prototype aircraft prior to committing to full production.

RDT&E is broken into multiple elements for which costs are derived. According to Corke (2002), these elements are:

- Airframe engineering
- Development Support
- Flight test aircraft, which is further broken into
    - engine and avionics
    - manufacturing labour
    - manufacturing materials
    - tooling
    - quality control
- Flight test operations
- Profit

As the Corke model takes as reference the DAPCA IV model, the basis for estimating the development cost is the Cost Estimating Relationships (CERs), using as aircraft performance parameters the following ones:

- The empty weight, We (units of pounds) and
- The maximum speed, V_{max} (units of knots)

Besides, these equations use coefficients in order to adjust these characteristics to the cost of existing aircraft in the data set considered. However, as these coefficients are estimated for 1986 dollars, they must be converted to present dollars using an appropriate escalation factor. It has been chosen the Consumer Price Index (CPI), as it is public information and it can be easily found on the internet. The model estimates the hours required for RDT&E by the engineering, tooling, manufacturing and quality control groups. There are multiplied by the appropriate hourly rates to yield costs. Development support, flight test and manufacturing material costs are directly estimated. Then, each of the phases is described:

- Airframe engineering involves the airframe design and analysis, wind tunnel testing, mock-ups, test engineering, and evaluation during the acquisition phase. It also includes analysis and incorporation of modifications material and process specifications and reliability analysis. The airframe engineering cost is first expressed as the total hours that are associated with this element. The hours are then converted to a cost based on an hourly rate for engineering.
- Development support is defined as the non-recurring manufacturing effort to support engineering during the RDT&E phase. This involves the labour and material required to produce mock-ups, test parts, and other items needed for the airframe design and development.
- The manufacturing labour costs are based on the number of hours that are needed to fabricate and assemble the major structural elements of the aircraft. It includes the labour associated with the installation of off-site or purchased manufactured components and the labour costs of manufacturing performed by subcontractors. The hours are converted to a cost based on an hourly rate for manufacturing labour.
- The manufacturing materials costs includes the raw materials, hardware, and equipment required for the fabrication and assembly of the aircraft.
- Tooling refers to jigs, fixtures, dies, and other special equipment that is used in the fabrication of the aircraft. The cost of tooling is first expressed in hours required for tool design, fabrication, and maintenance. The hours for tooling are converted to a cost based on an hourly rate for tooling labour.
- Quality control is the task of inspecting fabricated and purchased parts and assemblies for defects and adherence to specifications. The time associated with quality control is related to the total number of labour costs. Again, the total hours are converted to a cost based on an hourly rate for quality control.
- The flight test costs include all the elements involved in conducting aircraft flight tests. It includes flight test engineering planning, data analysis, instrumentation, fuel, test pilot salary, facilities, and insurance. The flight tests are essential for establishing the aircraft operation envelope and flying characteristics.
- The engine and avionics are assumed to be items in which the cost is presumably known from the manufacturer and they are not included in cost estimation.
- Finally, profit is based on a fixed percentage of the total cost of all of the elements in the RDT&E phase. A typical profit value is 10%, which will be the value used for calculations.

Hourly rates

As mentioned, the hours estimated in some of the CERs are converted to a cost based on an appropriate hourly rate for the labour. These hourly rates include the total cost made up of salaries, overhead, benefits, administrative expenses, and miscellaneous direct charges. The following table shows the hourly rates for airframe engineering, tooling, manufacturing, and quality control for the year 1986.

Year	Engineering	Tooling	Manufacturing	Quality control

1986	59,10 $/hour	61,70 $/hour	55,40 $/hours	50,10 $/hour

These values must be converted to present dollars, by using an appropriate escalation factor. In this case, the factor considered is the Consumer Price Index (CPI) which is information provided by the U.S. Department of Labour Bureau of Labour Statistics[79]. As an example, the conversion from 1986 to 2018 dollars is made as follows:

CPI (1986) = 109.6

CPI (2018) = 251.107

Considering the previous values, the escalation factor obtained for the year 2018 taking as a base the CPI is:

$$CPI\ (1986 - 2018) = 2{,}29$$

With this factor, the 1986 hourly rates are converted to 2018 dollars.

Year	Engineering	Tooling	Manufacturing	Quality control
2018	135,41 $/hour	141,36 $/hour	126,93 $/hours	114,79 $/hour

In addition, since CPI values are not available beyond 2018, a linear curve fit has been applied to the data in order to aid in making projections for future years. In this way, it will be possible to estimate hourly rates for the year in which the new aircraft program development is expected, which is planning for the 2025 timeframe according to Boeing.

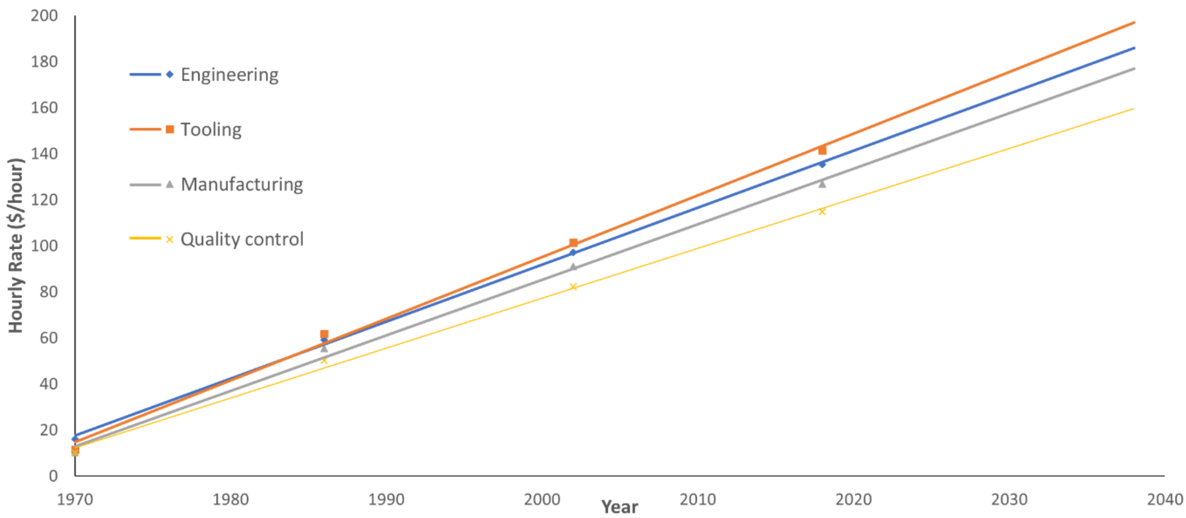


Figure 13.73. Hourly rates projection

Based on the previous graphic, the linear relations are:

$$C_{Engineering} = 2{,}4758 * x - 4859{,}8$$

$$C_{Tooling} = 2{,}6823 * x - 5269{,}5$$

$$C_{Manufacturing} = 2{,}4145 * x - 4743{,}7$$

$$C_{Quality\ control} = 2{,}1656 * x - 4253{,}9$$

Where x corresponds to the year. By inserting the year in the formulas, the results obtained are the hourly rates in dollars per hour for the year introduced. According to this, the hourly rates for the year 2025 are:

Year	Engineering	Tooling	Manufacturing	Quality control
2025	153,69 $/hour	162,16 $/hour	145,66 $/hours	131,44 $/hour

Finally, once obtained the hourly rates for the target year, they are used to convert the hour values associated with their respective elements to the cost in dollars.

Re-engine non-recurring costs

In case that the company's strategy consists of re-reengining an existing aircraft instead of developing a new one, the cost may be significantly lower, as much of the work can be taken from the earlier program and modified rather than generated from scratch. After reviewing several aircraft cost programs with their modified and improved versions, it has been estimated that the cost of re-reengining corresponds to the 30% of the cost of developing the same aircraft from the beginning[78].

Recurring Costs of Production

Aircraft manufacturing costs are considered recurring costs, since they are based upon the number of aircraft produced, and as such, they are assumed to be subject to a learning curve. This phenomenon is characterized in aircraft production by a significant decrease in unit cost as additional aircraft are built. The decrease is most noticeable early in the production run and eventually decays to a negligible level when unit cost remains roughly constant.

The learning curve depends on a parameter known as "slope", which describes the magnitude of the learning curve effect mentioned above. A slope of 100% indicates no learning (the initial unit cost remains constant throughout the production run). As the value decreases, the learning effect grows stronger. As described by Raymer (1992), the learning curve is modelled as:

$$C_{q_i} = c_1 * q_i^{\frac{\ln \beta}{\ln 2}}$$

where C_{q_i} is the unit production cost of the ith unit produced, c_1 is the theoretical first unit cost (TFUC), q_i is the number of units produced, and β is the learning curve slope.

Aircraft production typically follows a 75-85% learning curve slope. For this study, it will be used a value of 85%, since it is a value generally accepted within the aerospace industry[78].

The theoretical first unit cost was estimated using the DAPCA IV model developed by Rand Corporation. This model allows estimating the total program cost for a production run of 100 units. The output was used to find an estimate of the unit cost for the 100th aircraft to be built. Then, this cost is converted to first unit cost, based on the learning curve assumption, in the same way as Markish (2002)[80].

The estimated cost of the B787 first unit obtained by this method is illustrated in Figure 13.74 as an example.

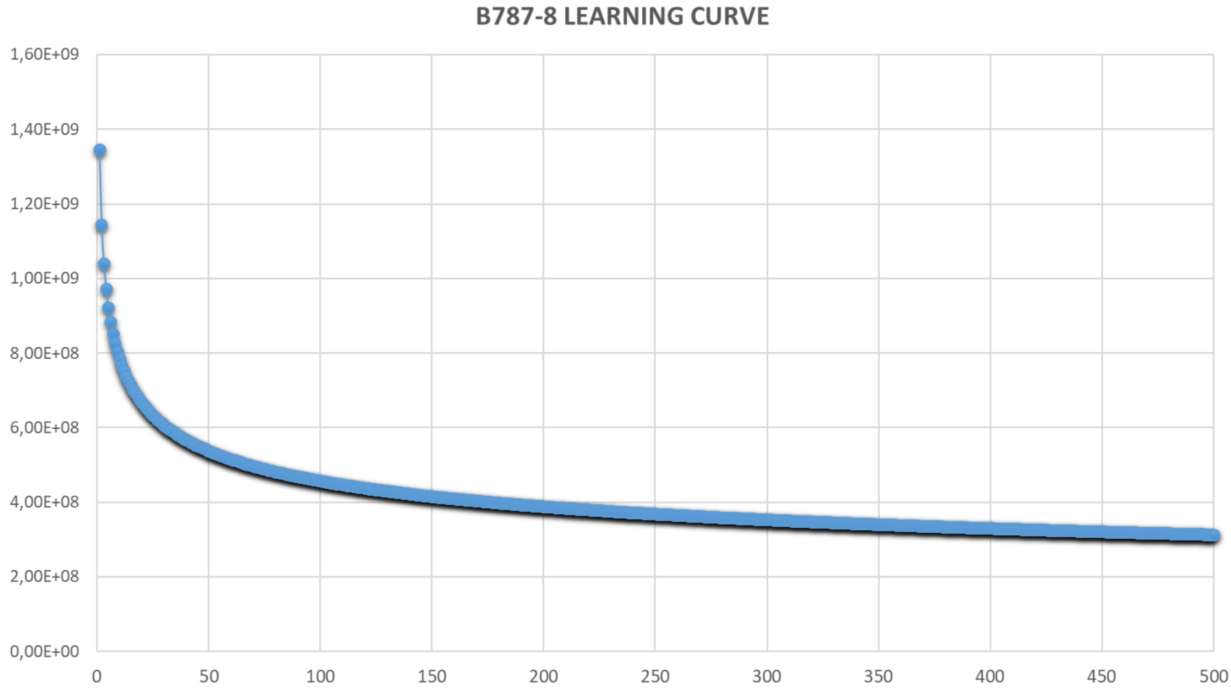


Figure 13.74. B787-8 production learning curve.

As can be seen from Figure 13.74, the first unit cost of the B787 was around 1,35 billion dollars with the corresponding conversion to 2019 dollars. It is a reasonable value taking into account that the production costs of an aircraft like the 787 are very high for the first units. With a learning curve of 85%, the cost for aircraft 100 is around 457 million dollars.

Due to the learning curve effect, it has no sense to compare between a new aircraft which has just entered production and an old aircraft which has already been produced in hundreds or thousands, since the cost per unit in both cases will be very different.

13.2.8.2 Aircraft Operation Cost Analysis

Over the course of an aircraft's operating life, there are several cost issues that represent a key factor for the airlines purchasing decisions. Typically, the operating costs are divided into Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). On the one hand, IOC are the costs related to the management strategies and level of service of the airline and include items such as the costs of sales and marketing, general and administrative costs, the costs of handling and meals, or the costs of maintenance and depreciation of the ground equipment and facilities[81]. On the other hand, the DOC elements are connected to the act of flying an aircraft, such as the fuel spent on a trip, the costs with crews, or the maintenance associated with the trip flown. The DOC, along with the Indirect Operating Costs (IOC), form the Total Operating Costs (TOC) of an airline or a particular aircraft. In this study, it will be only calculated the Direct Operating Costs, since these costs are highly dependent on the design of the aircraft.

For the DOC calculation, the TU Berlin DOC Method [82] has been chosen, due to its simplicity as it allows to estimate Direct Operating Costs of an aircraft based on data which are public. This model divides DOC into the following main areas:

- Capital costs, where it is included the costs of depreciation, insurance and interest
- Fuel costs
- Fees, including navigation, landing and ground handling taxes
- Maintenance costs, both for the airframe and engines, which take into account the labour costs, the costs of materials and the overhead burden costs.
- Crew, which includes cockpit crew and flight attendants

The TU Berlin DOC Method provides the results in 2010 Euro so that it will be necessary to transform them to 2010 US$ using the average exchange rate of that year and then from 2010 to 2018 dollars using the Consumer Price Index which is available at the US Bureau of Labour Statistics website.

In the following points, the methodology followed to calculate each component of the Direct Operating Cost is described. Subsequently, these costs are calculated for two aircraft as a comparative example.

Capital costs

The Capital costs are related to the depreciation, insurance and interest costs, which are dependent in turn on the aircraft price. Therefore, the cost of acquisition of the aircraft is used to compute the previous costs.

Two relevant parameters to be considered to calculate depreciation cost are the useful life of the aircraft and its residual value. On the one hand, the most common values for useful aircraft life are in the interval 15 to 20 years. In this study, it will be considered the 20-year mark. On the other hand, the residual value is the amount that an airline expects to receive for the aircraft after the assumed useful life, not accounting for inflation. It is a value which depends on the conditions of the specified aircraft, the second-hand market as well as maintenance conditions. The residual values mostly used are in the range of 0-10% for passenger aircraft. In this study, it will be used thus the 10% value. Besides, the insurance rate used in the model is 0,5% and it is considered an annual interest rate of 5%.

Fuel Costs

Today, fuel costs represent a significant part of the operating costs of an aircraft. In fact, the aircraft fuel efficiency is, along with range and seat capacity, one of the most important factors on determining how much is an airline willing to pay for an aircraft. That is, an aircraft spending less fuel for the same number of passengers carried and miles flown than another one is expected to bring more value to the airline company.

The calculation of the fuel costs follows a methodology relatively simple, which consists in multiplying the fuel price by fuel consumption. In order to obtain the total amount of fuel burned per year, annual utilization must be calculated. TU Berlin DOC method calculates the yearly utilization based on the average flight time of each trip, an additional time that accounts for turnaround times, and the downtime due to maintenance checks and night curfew. However, the utilization values per each aircraft model used in this study have been obtained from the Airline Monitor reports available on its web page. Within these reports, it is included data about the utilization (in block hours per day) per aircraft model as well as the fuel consumption (in gallons per block hour). With this data, it is possible to calculate the total amount of fuel burned per year, which is multiplied then by the fuel price.

The main problem of this method lies in the estimation of the fuel price in the long run, as it is very volatile, and it can change drastically from year to year depending on the multitude factors. However, as the purpose of this study is to perform a long-term forecast in order to analyse the impact of a new mid-size aircraft in the aerospace market, it is essential to dispose of forecast data to contemplate different fuel price scenarios as they are a relevant component of the DOC. These projections have been obtained from the U.S Energy Information Administration (EIA) web page [83], where it is included projections until 2050 considering both optimistic and pessimistic scenarios as well as a base reference scenario.

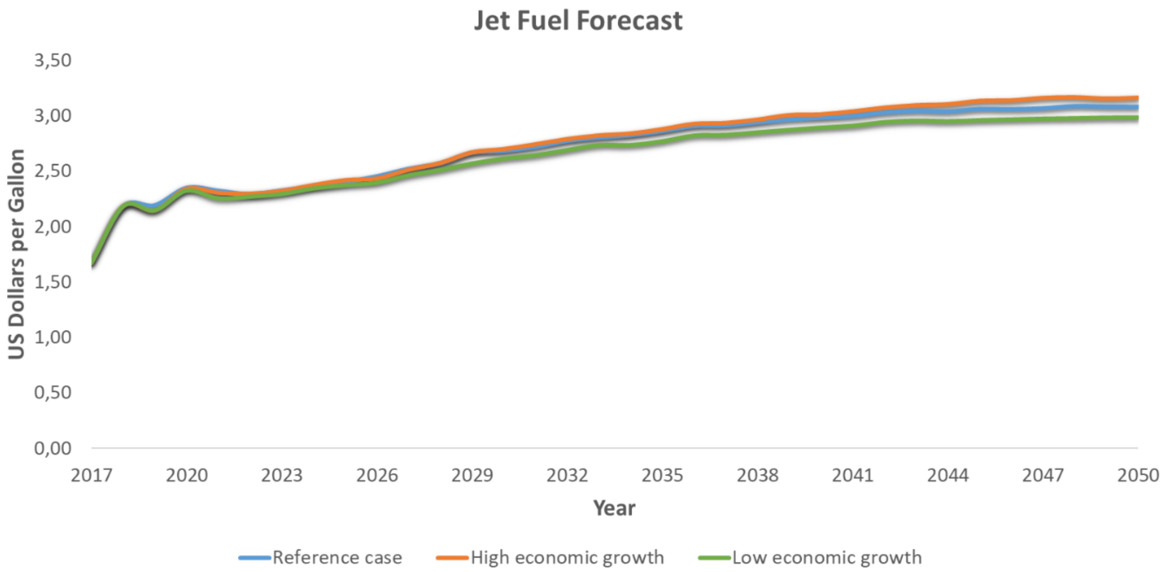


Figure 13.75. Jet fuel price forecast under different scenarios.

Fees costs

The fees calculation is divided into navigation, ground handling and landing taxes:

- Landing fees are charges paid by the airlines to the airports for each landing that an aircraft performs at that airport. Its calculation depends essentially on the aircraft maximum take-off weight and the number of flight cycles in one year, which are estimated based on aircraft utilization in block hours and the average flight time of each trip in hours. Then, these values are multiplied by the landing fee rate, which corresponds with 0,01 €/kg according to the model.
- The navigation fees are charged by air traffic authorities of each country to pay for the costs of providing air navigation services, including costs of maintenance, operation, management and administration of that service. In the TU Berlin method, navigation fees calculation depends on the maximum take-off weight and the distance flown and, additionally, applies different rates

depending on the area the aircraft is flying (domestic European flights, transatlantic flights or far east flights).

- Finally, ground handling fees calculation depends on the payload carried in terms of kilograms, which is calculated considering a load factor of 80% and an average weight per passenger of 100 Kg. This value is multiplied by the number of flight cycles in one year and the ground handling fee rate, which corresponds with 0,1 €/kg according to the model.

Maintenance costs

The maintenance of an aircraft is made through various checks, which usually depend on the number of hours flown or on the flight cycles, with different levels of complexity and with different time schedules. They can go from simple transit checks after every flight, which last around 15 minutes to half an hour, to major maintenance processes where the aircraft has to be completely taken apart for a thorough inspection of all of its parts, and these can last as much as 2 or 3 months. In addition, the maintenance schedules can vary from one airline to another, and from one aircraft model to another. Therefore, the maintenance process is complex, not always predictable and not homogeneous over time.

The costs involved in this component are, in a simplified way, the labour, material and burden costs for both the airframe and the engines maintenances. Burden costs are associated with overhead costs, administration costs or holding of spare parts, among others. TU Berlin method estimates a burden cost of two times the labour costs, both for the airframe maintenance and engine maintenance.

The estimation of the airframe maintenance costs is based on the operating empty weight and the number of flight cycles. Regarding the engines maintenance costs calculation, the Sea Level Static Thrust (SLST) and the number of engines on the aircraft are the parameters used.

Crew costs

The last component to be considered in the TU Berlin method is the crew costs, which are divided into cockpit crew and flight attendants cost. The model assumes standard salaries per year, which are different depending on the case. In addition, the number of flight attendants per flight is calculated based on the aircraft seat count. These values are multiplied by a crew complement, which considers the number of crews per aircraft.

Operating costs distribution

The DOC method proposed is useful to give an estimation of the total operating costs of a determined aircraft within specific operation conditions. Moreover, only a few input parameters are required: Aircraft physical data such as the MTOW[4], OEW[5], engine weight, SLST, and financial parameters such as the fuel price and the depreciation rate, which can be obtained from the wide range of statistical data available in the literature.

For calculating the costs, an average stage length is assumed. This is the mean distance the aircraft is supposed to fly within a year and the number of flight cycles that are expected to perform. This

[4] Maximun Take-off Weight

[5] Operating Empty Weight

parameter is directly related to the utilization since a supplement of block time is assumed for every flight stage.

Figure 13.76 shows the distribution of the operating costs for four different aircraft models: the 20-year Boeing 767 wide-body aircraft, the last generation wide-body Airbus A350 and the newest update the US and EU single-aisle airplanes, the Airbus A321neo LR (long-range), and the Boeing 737 MAX-8.

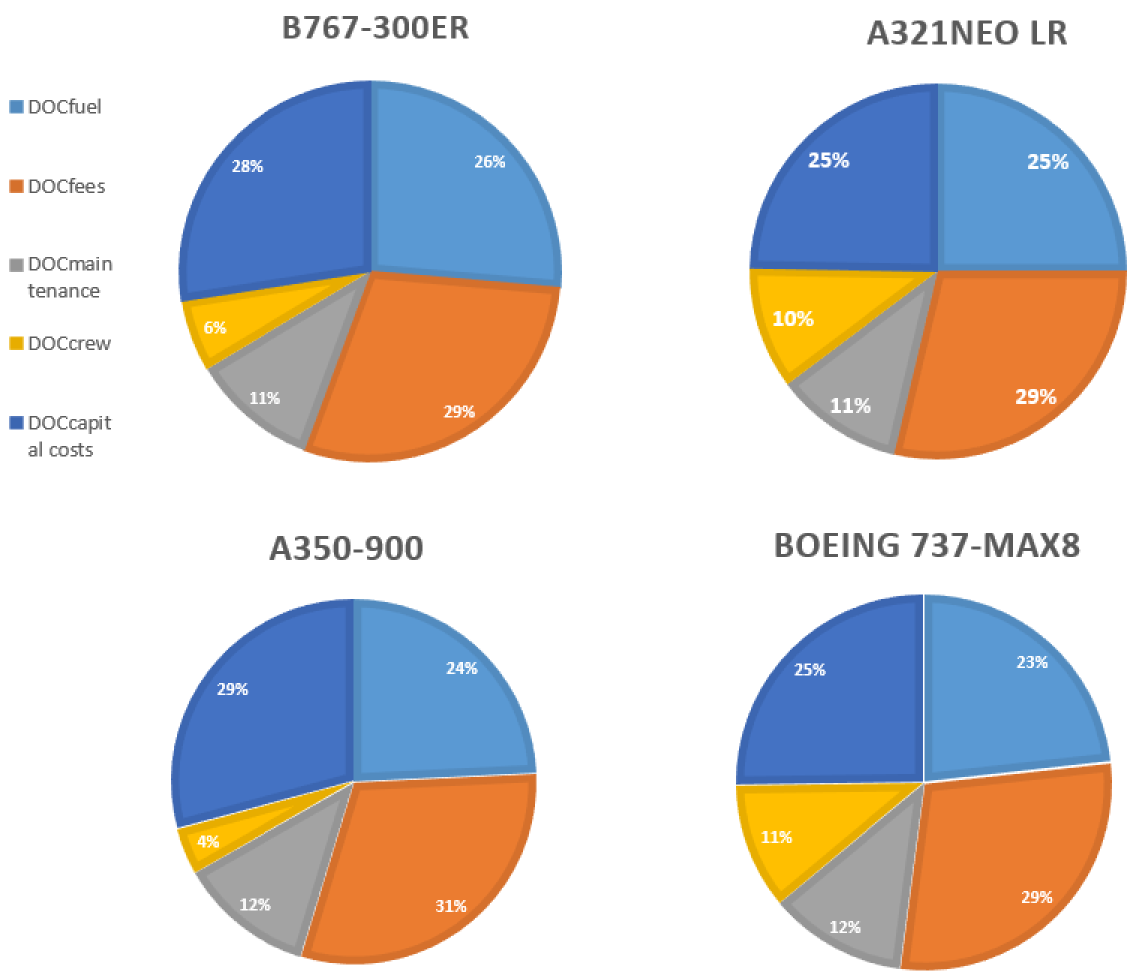


Figure 13.76. Operating costs distribution for four different aircraft models

As can be seen in the figure, cost distribution is very similar for every model, and only slight variations are appreciated. The total yearly maintenance costs around 10% of the global costs, the crew is between 6-10% of the total costs, usually lower for wide-body aircraft, due to the higher rate of passengers-crew members. The fuel costs are more or less similar in every type of aircraft, representing about 25% of the total. Another important part of an aircraft (about the 30%) operating costs is the fees, including airport fees, ground handling and navigation fees. This part of the costs is usually dependent on the size and the weight of the aircraft, although, in nominal terms, it represents a similar percentage for every aircraft model. Lastly, the greatest part of the costs is usually represented by the capital costs, which are normally heavier for wide-body aircraft, rounding 25-30%.

The yearly direct operating costs of an aircraft are between 20-25 M€ for single-aisle aircraft and between 45-60 M€ for wide-body airplanes. The use of absolute numbers does not allow a good comparison between models since the size and weight of the aircraft determine both the costs and the number of passengers carried. For this reason, the Cost per Available Seat Mile (CASM) is used. This can be calculated as:

$$CASM = \frac{DOC}{ASM} = \frac{DOC}{SL \cdot n_{seats} \cdot FC},$$

where SL is the average stage length, n_{seats} the number of available seats and FC the number of flight cycles per year. The $CASM$ represents the cost of carrying a passenger over a nautical mile. Therefore, it represents a useful way to compare different-sized aircraft costs for different flight lengths.

The following table shows the results of the direct operating costs estimated using the TU Berlin DOC method for different flight lengths. For representing the $CASM$, a standard two-class configuration has been assumed for single-aisle aircraft (B757, A321...) and a standard three-class configuration for big wide-body airplanes (B777, A350...).

Aircraft	*DOC (1000 nm) [M$]*	*CASM (1000 nm) [$ cents]*	*DOC (3000 nm) [M$]*	*CASM (1000 nm) [$ cents]*
B757-200	28.1	8.56	2.34E+01	7.1
B767-300ER	39.6	8.87	3.25E+01	7.3
A321LR	24.8	7.70	2.06E+01	6.4
B737 MAX 8	22.0	8.00	1.83E+01	6.7
A330-200	54.5	10.07	4.40E+01	8.1
A330-300	58.3	9.61	4.72E+01	7.8
A330-900N	58.4	9.29	4.68E+01	7.5
B787-8	54.4	9.67	4.37E+01	7.8
B787-9	59.7	8.85	4.74E+01	7.0
A350 - 900	59.6	9.24	4.79E+01	7.4
B777-200ER	65.4	9.57	5.26E+01	7.7
B777-300ER	71.7	9.25	5.77E+01	7.4

Table 13.17. Yearly direct operating costs for different aircraft in two flight length cases

As it is visible from the table, the $CASM$ is very similar from one model to another, and no big differences are appreciated. The next generation aircraft such as the A330 neo or the B787 have lower operating costs due to the improvements made in efficiency, achieving almost a 15% savings regarding the last generation. Nevertheless, as shown in Figure 13.76, fuel costs only represent about 20% of the total costs. Thus, fuel efficiency improvements are not sufficient reason by itself for airlines to decide to change their fleet.

13.2.8.3 Market share model

The analysis of the routes flown by aircraft within the Middle of the Market performed in Section has allowed estimating the market share of this segment in 2018. According to the data obtained, Boeing is currently dominating the Middle of the Market segment, considering medium-haul routes (Figure 13.77).

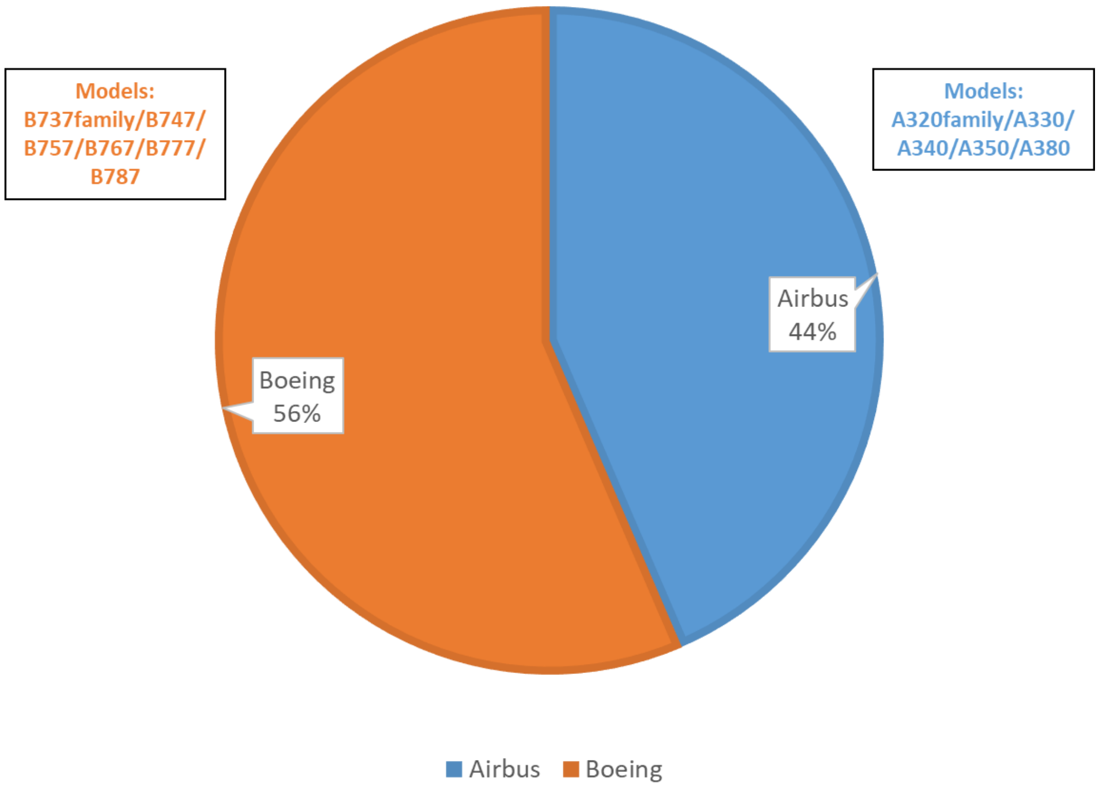


Figure 13.77. Boeing/Airbus market share in the Middle of the Market (2018)

Taking as a base this market share obtained through routes analysis, the market share model for the 2020-2040 period has been developed. The methodology of this model is based on the use of tables in which it is included the market share percentage of the aircraft that will compete in the Middle of the Market for the period considered. These aircraft are placed in the first line of the table while the aircraft that are currently operating in the MoM segment is placed in the first column of the table. The percentages of the table represent the market share that each aircraft (first line) absorb from the current aircraft (first column). The procedure followed takes into account that, except for the cases of the A350 and B787, the rest of the current models are expected to be replaced in the following years as discussed in section 13.2.2.4.

Combining these percentages with the current market share that these aircraft possess gives as a final result the market share for each aircraft considered as a potential competitor in the Middle of the Market for the 2020-2040 period. This process is made for a range between 2500-4500 nm divided into segments of 500 nm (i.e. 2500-3000 nm, 3000-3500 nm…) since the market share estimated with routes analysis has been obtained in a similar way, providing for this method more accuracy.

Distance: 2500-3000 nm	A330-900NEO	A350-900	B737-MAX	B777-X	B787-900	A321 neo LR	Boeing NMA
A320 family	0%	0%	0%	0%	0%	100%	0%
A330-200	15%	5%	40%	0%	0%	40%	0%
A330-300	15%	5%	40%	0%	0%	40%	0%
A340	12%	8%	40%	0%	0%	40%	0%
A350	0%	20%	40%	0%	0%	40%	0%
A380-800	12%	8%	40%	0%	0%	40%	0%
B737-700/800/900	0%	0%	100%	0%	0%	0%	0%
B747	0%	0%	40%	10%	10%	40%	0%
B757	5%	5%	45%	5%	5%	35%	0%
B767	5%	5%	45%	5%	5%	35%	0%
B777	0%	0%	40%	15%	5%	40%	0%
B787	0%	0%	40%	0%	20%	40%	0%

Table 13.18: MoM aircraft market share (2040) between 2500-3000 nm

The percentages of the table have been assigned based on operating costs values, which have been calculated following the procedure explained in section 13.2.8.2. This method provides a comparison of cost efficiency between aircraft, being represented the improvements in green colour. Red cells represent those cases in which the aircraft is less efficient than its competitor. The table shows that most of the aircraft considered for the 2020-2040 period will be more efficient in operating costs compared to current aircraft, which is reasonable as they are more modern and advanced versions.

	A350	B787	A321neoLR	A330neo	B777X	B737MAX 8	B797
A350-900	0,070	0%	30%	3%	8%	30%	17%
B787-900	0%	0,070	30%	3%	8%	30%	17%
B757	-15%	-15%	11%	-12%	-8%	11%	0%
B767	-11%	-11%	16%	-8%	-4%	16%	5%
A330-200	14%	14%	48%	17%	22%	48%	33%
A330-300	8%	8%	40%	11%	16%	40%	26%
A340	19%	19%	55%	22%	28%	55%	39%
B747	8%	8%	41%	11%	17%	41%	27%
B777-200	2%	3%	33%	5%	10%	34%	20%
B777-300	-3%	-3%	26%	-1%	4%	26%	13%
A380	9%	9%	42%	12%	17%	42%	28%

Table 13.19. Comparison of operation costs between aircraft

Despite the simplicity of the model used to calculate the operation costs, the results obtained can be used to estimate the magnitude ordering of efficiency improvements between aircraft. Based on this table, it can be extracted two main hypotheses:

- The A321neo LR and B737 MAX 8 are the most efficient aircraft, with significant differences compared to other aircraft. Therefore, they will absorb a great market share up to a maximum of 80% both together. If only a single aircraft is more efficient, it would absorb a maximum of 50% of the market share.
- There are no significant differences in operating costs between the A350, B787, A330neo and B777X. Therefore, the market will be distributed between them equally.

However, in addition to cost efficiency, it is necessary to considerer other relevant aspects for market share estimation. For example, airlines are generally committed to one's manufacturer's product line. That is, airlines usually prefer a fleet composed of aircraft from the same family to reduce training and maintenance costs, as well as the cost of spare part inventories. Therefore, it is expected that only substantial improvements in cost efficiency will be enough to convince airlines to switch. Then, it is assumed that some airlines will remain loyal to specific manufacturers. Taking this into account, to distribute the market share of an Airbus aircraft that is expected to be replaced in the near future, like the A340, it will be assigned more percentage to Airbus models as it is more likely that airlines will prefer a model of the same product line.

Other hypotheses related to airlines' loyalty which have been applied in market share distribution is the case of re-engine aircraft. Some models like the A330neo or B777X are more efficient modifications of the previous aircraft. In this case, it is likely that airlines, which have old versions available, for example, the A330-200 or A330-300, will prefer the A330neo, which is the newest version of the aircraft. As modified versions are very similar to the original aircraft, except for the engines which are more efficient, airlines can save costs in terms of maintenance and crew training. Fort this reason, when the market of the previous versions is distributed, it will be assigned more market share percentage to those aircraft which are re-engine versions.

As it was said before, the market share is assigned by 500 nm range segments beginning with 2500 nm till 4500 nm. As range increases, airlines will be more interested in larger aircraft which have more range capabilities, according to the market share obtain through routes analysis. For this reason, a percentage of a 10% will be added for each segment in favour of larger aircraft, taking this percentage from small aircraft such as the B737 MAX 8 or A321neoLR. That is, as the range of segments analysed increases, more market share will be taken from narrow-body aircraft and it will be assigned to wide-body aircraft.

On the other side, as the B787 and A350 are expected to remain in the market for the considered period, a minimum percentage of 20% will be assigned for those airlines which are not willing to switch to another model. This percentage will increase a 10% each time the range increases as these models are optimised for longer distances.

Finally, to distribute the market share, other hypotheses will be considered:

- It is established a minimum market share percentage of 5%.
- It is assumed that market share of A320 and B737 families are absorbed completely by their successors, the A321neoLR and B737 MAX 8 respectively since they are much more efficient.
- B757/B767: as this fleet is expected to be retired in the following years, its market must be distributed. It will be assigned more percentage to the new Boeing airplane, the B797, as it will be designed specifically to replace this fleet.

Table 13.Table 13.20 summarizes all the hypotheses used to develop the market-share model.

Market share hypothesis	Percentage assigned
• Two or more aircraft with significant cost improvements	A maximum of 80%
• One aircraft with significant cost improvements	A maximum of 50%
• The market share of A320 and B737 families are completely absorbed by their newest versions, the A321neoLR and B737 MAX 8	100%
• No significant differences in cost efficiency between aircraft	Equally distributed
• To distribute the market share of an aircraft, it will be assigned more percentage to the same manufacturer models	A minimum of 5%
• It is stablished a minimum market share percentage	5%
• It will be assigned more percentage to the B797 in the case B757/B767 fleet market share distribution	20%
• It will be assigned more market share percentage to those aircraft which are re-engine versions when the market share of previous models is distributed	A minimum of 10%
• A percentage will be added as the range segment increases in favour of larger aircraft	A 10%
• A percentage of loyalty is assigned to the models A350 and B787	A minimum of 20%

Table 13.20: Market share model hypothesis

13.2.8.4 Aircraft sales price landscape

Aircraft sale price is an important factor within aircraft's lifecycle cost, and it represents a significant role in the operating costs of a company since the cost incurred in its purchases will directly influence the capital costs (depreciation, insurance and interests). For this reason, the acquisition price of an aircraft can significantly affect airlines purchasing decisions.

Generally, the aircraft is set with the objective of recovering gradually the development investment with every unit sold, so that the money spent on this phase must be divided by a given number of aircraft, according to the manufacturer expected sales. The production costs must then be summed to that value. This will yield the cost of the aircraft and adding a profit margin for the manufacturer company will finally lead to the aircraft selling price.

However, an aircraft sale price also depends on other factors, such as aircraft operational performance. If an aircraft can provide significant operational savings, it can suppose a differentiating factor to convince airlines to switch to the aircraft's competitor. Additionally, if the aircraft performance improvements are significant, manufacturers could increase price sale proportionally to the operational reductions expected, as customers will be willing to pay more, and its price will be higher than of its competitors. Other factors that can affect aircraft price are performance and physical characteristics, as no single aircraft has exactly the same characteristics as another one. Nevertheless, aircraft which can be fit into a certain segment usually own similar operational characteristics and, as a consequence, the selling prices will most likely also be of the same magnitude. For this reason, as the main competitor of the new Boeing NMA is expected to be the A321neo long- range, it is likely that their prices may be similar, but this could not be the case if the 797 is finally a twin-aisle model as it is expected, since this type of aircraft is usually more expensive and manufacturers must recover the investment, resulting in higher selling price. However, even if the new 797 aircraft is a twin-aisle model, Boeing will have to consider carefully the price as it may affect to expected sales if it is much higher than that of the A321LR.

On the other hand, one point that is of great importance to discuss is the discounts that aircraft manufacturers offer to their customers. It is known that aircraft manufacturers offer discounts that can vary from a few percentage points to more than 50% of the list prices[84]. Generally, the higher is the number of aircraft ordered by a client, the higher are discounts got. However, discounts magnitudes vary from one client to another: those who have a stronger bond to the manufacturer are able to get higher discounts, while those who have not so much experience in buying aircraft usually have lower discounts. The discounts also vary from manufacturer to manufacturer and from one aircraft family to another, it depends on how many aircraft are going to be produced and sold.

However, the main difficulty with discounts is the fact that they are not public, which creates a problem for estimation. Table 13.21 shows an estimation of the discount applied by both companies in 2017, taking as a base the order book value published.

Aircraft	List price (USD millions)	Market value (USD millions)	Discount
A380	432.6	236.5	45%
B777-300Er	339.6	154.8	54%
A350-900	308.1	150	51%
B787-9	264.6	142.8	46%
B787-8	224.6	117.1	48%
A330-300	256.4	109.5	57%
A330-200	231.5	86.6	63%
A321	114.9	52.5	54%

Aircraft	List price (USD millions)	Market value (USD millions)	Discount
A320neo	107.3	48.5	55%
B737-900ER	101.9	48.1	53%
B737-800	96	46.5	52%
A320	98	44.4	55%
A319	89.6	37.3	58%
B737-700	80.6	35.3	56%

Table 13.21. Estimation of discounts applied by Airbus and Boeing in 2017[84].

Other companies like Bombardier o Embraer are not able to offer aircraft with such discounts since the return on investment is divided by a much smaller number of aircraft. Although these companies offer aircraft more efficient and with lower list prices, most airlines still prefer Airbus and Boeing aircraft, as they perceive commonality with the rest of their fleet as a sufficiently strong cost- saving factor. Table 13.22 shows the 2018 list prices of Airbus and Boeing, which is available on their websites.

Boeing		Airbus	
Model	2018 (USD millions)	Model	2018 (USD millions)
A220-100	81	737-700	89,1
A220-300	91,5	737-800	106,1
A318	77,4	737-900ER	112,6
A319	92,3	737 MAX 7	99,7
A320	101	737 MAX 8	121,6
A321	118,3	737 MAX 200	124,8
A319neo	101,5	737 MAX 9	128,9
A320neo	110,6	737 MAX 10	134,9
A321neo	129,5	747-8	418,4
A330-200	238,5	747-8 Freighter	419,2
A330-800neo	259,9	767-2C	-
A330-200 Freighter	241,7	767-300ER	217,9
A330-300	264,2	767-300 Freighter	220,3
A330-900neo	296,4	777-200ER	306,6
A340-300	-	777-200LR	346,9
A340-500	-	777-300ER	375,5
A340-600	-	777 Freighter	352,3
A350-800	280,6	777-8	410,2
A350-900	317,4	777-9	442,2
A350-1000	366,5	787-8	248,3
A380	445,6	787-9	292,5
		787-10	338,4

Table 13.22. Airbus and Boeing 2018 list prices

13.2.8.5 Net Present Value as Aircraft Project Valuation Model

One of the most effective ways to financially evaluate medium- and long-term decisions of aircraft manufacturers are using the Net Present Value of their investments, after having performed a demand analysis such as in section 13.2.7.2. Irwin *et. al* [85] used the Net Present Value as the objective function that manufacturers use to maximize their mark-ups. Considering the company f, the objective function of one of its products, i, is given by:

$$\pi_{fi} = \sum_{t=1}^{n} (\delta_t [p_{it} q_{it}(p) - c_{it} q_{it}(p) - I_{it}] - I_{i0}),$$

where δ_t is the discount rate at the period of time t, p_t is the price of the product at the period of time, I_{i0} the initial investment required (i.e. R&D and manufacturing costs), I_{it} are the fixed costs due to capacity, c_t is the cost of the product at the period of time t and q_t the quantity sold at the period t, which is the product of the manufacturer's market share and the total expected demand.

It is necessary to remark that other authors like Irwin *et. al* [85] calculate the payoff considering the uncertainties of the demand and jet fuel prices so that the Net Present Value is calculated as a statistical distribution with different probabilities for the multiple possible paths. Thus, the value used for the payoff function is the expected value of the NPV, $E[NPV]$, instead. For this case study, a simplified calculation form of the function was assumed, neglecting these uncertainties of the demand and jet fuel prices.

This objective function accounts for two characteristics of the aircraft industry: learning by doing in production and multi-product firms. First, the existence of learning by doing implies that a firm's choices today affect the costs of production in the future through-accumulated experience. Firms likely consider these intertemporal linkages in their profit-maximizing decision. In particular, these dynamic considerations might make it profitable for a firm to price below marginal cost during the initial stages of production in order to quickly accumulate the experience and reduce the future cost of production. Second, aerospace manufacturers such as Airbus and Boeing are multi-product firms that are selling several products during most time periods. Thus, when Boeing considers lowering the price of one of its products, this will not only reduce the market share of Airbus's products but might also undercut the sales of Boeing's other products. Boeing might then lower its prices by less than in a situation when it only sells one product. Assuming that aerospace firms are multi-product companies, the global payoff function of the company f may be considered as the sum of every firm's product in the market as:

$$\pi_f = \sum_{i=1}^{m} \left[\sum_{t=1}^{n} (\delta_t [p_{it} q_{it}(p) - c_{it} q_{it}(p) - I_{it}] - I_{i0}) \right],$$

where m is the number of products of the firm.

There are many input factors influencing the payoff as shown in the previous section of this chapter. The R&D investment, the cost of the first unit or the selling price are some of the variables that affect the most to the payoff function. These parameters are summarized in Table 13.23, alongside the reference, low and high values for the evaluation of the Boeing NMA program and it will be used later for the sensitivity analysis.

Parameter	Low	Ref	High
Learning curve slope	80%	85%	90%
First Unit Cost [mill. US$]	700	800	900
Capacity Fixed Costs [mill. US$/month]	0	3	5
R&D Investment [mill. US$]	10000	12000	14000
Discount rate	6.8%	8.0%	9.2%
Expansion costs [mill. US$]	10	20	30
Demand [units]	2500	3200	3900
Price [mill. US$]	160.0	180.0	200.0

Table 13.23. Boeing NMA Aircraft valuation model input parameters

Sensitivity analysis

A sensitivity analysis was performed to determine whether the aircraft program valuation model is robust, within the high and low range of input parameters listed in Table 13.23. Figure 13.78 shows that the aircraft program valuation model is more sensitive to the learning curve slope, selling price and theoretical first unit cost (TFUC) assumptions. In comparison, the development cost and discount rate assumptions have little impact on the NPV of the new aircraft program.

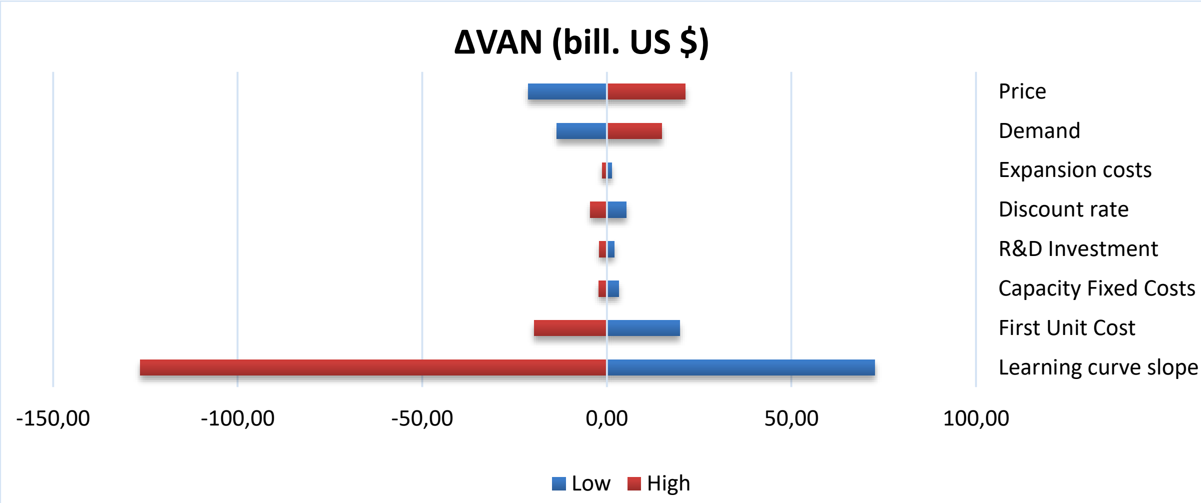


Figure 13.78. Sensitivity analysis of aircraft program valuation

The reference values of these parameters will be used later for game theory analysis. The model was tested varying the rank ordering of the parameters slightly around the reference values. The result of the game was only affected by the extreme change of the input parameters (such as the Learning curve slope).

13.2.9 Key success factors for a new MoM aircraft

Currently available options operated in the Middle of the Market are aircraft designed for another kind of mission that can operate in this segment as well. Not only the range and number of passengers are the influencing parameters of a potential NMA, but also its operating cost, configuration and the expectations of revenue the manufacturer has. Some of the success factors identified by PARE project are discussed hereafter, including where the other designs fall short and which gaps, if there are, need to be covered by a new aircraft.

13.2.9.1 Key features of the proposed design

The new proposed aircraft would assimilate the 767 in shape and size but not in capabilities. It should be more fuel-efficient and offer more comfort and flexibility to customers as well as not being oversized for its main mission.

Range and performance

Boeing mid-size aircraft tends to be a replacement of the B757 and B767 models. During the last 15 years, both Boeing and Airbus have counted on several stretched versions of their single-aisle short-range aircraft, the B737 and the A320. These models match the capabilities of the Boeing 757 mid-size aircraft respecting to passenger-carrying capabilities and even provide longer range than the B757. Nevertheless, they have lagged in other areas such as short-runway performance or high altitude climbing. The A320 and B737 have done very well, but they are two programs of which potential is reaching limits and there is definitely a gap that needs to be covered.

On the wide-body segment, the planes flying those 5000 nm routes are either undated, like the 767 with a more than 20 years old design, or too heavy or, like the 787 case, designed for flying more than 14 hours. The new MMA should be designed for flying no more than 5000 nm, approximately. Thus, it will be a lighter option for offering better economics.

Operating cost

The new mid-size aircraft should match the operating costs of a single-aisle with the capacity of a wide-body aircraft. The operating costs are an important factor for airlines to take into account. This new mid-size aircraft has to capture some narrow-body demand and to do so, it has to offer similar economics. The old model Boeing 757-200 offers an average cost per available seat mile (CASM) of $7.85, against the A321-200 $7.10. On the other hand, the Airbus' stretched version of the A320 offers fewer seats than the B757. The new mid-size aircraft should carry 220-280 passengers and offer a lower CASM than the previous B757.

Better fuel efficiency would result in savings for the operators, but this has to be achieved by newer technologies that might not arrive on time. An insight over the engines' technology problems is performed in the next chapter.

Apart from this, Boeing has been studying the feasibility of adding the necessary technology to the aircraft to be piloted by just one officer, according to [86]. This would result in great crew savings for the airline but has the drawback of not being ready until, almost, ten years. Nevertheless, this asset could make the new Boeing NMA design to stand out among the rest of aircraft in the market.

Single-aisle vs twin-aisle configuration

To capture the gap, the new mid-size aircraft should carry about 220-280 passengers in a typical 2-class configuration, a bit more than longest versions of short-range narrow-body aircraft. Making it single-aisle would mean a non-feasible too long fuselage. The solution then would be to offer a wide-body aircraft. Boeing is studying the possibility of including an elliptical-section fuselage that allows double aisle configuration and nearly single-aisle economics.

Boeing's proposal goes to the wide-body configuration due to several reasons. First, because of passenger comfort. According to Boeing [87], narrow-body aircraft are not feasible for long-haul routes due to the incommodity of the passengers. This is why the manufacturer aims to develop a new design that stands out in this factor. Another reason is the boarding time. Wide-body configuration allows boarding much faster than a narrow-body due to the multiple gates available.

Aftermarket

One of the key factors that directly influence the success of a new aircraft is not only focusing on the sales but also making money out of it to keep it flying. The initial purchase of a jet represents only 30% of the lifetime cost of operating aircraft. The resting 70% comes from maintenance, fuel costs, crew and more. For a manufacturer, the business of selling spare parts along the lifetime of an airplane is quite important. Therefore, if the aircraft is designed to keep flying for a long time, this aftermarket will be an important part of the business.

Many parts of a newly manufactured aircraft are coming from external suppliers: engines, APU, landing gear… etc. Taking some of these spare parts inside will allow a company to win aftermarket share. Nevertheless, this involves some risk since engineering work and cost have to be assumed by the manufacturer.

Regarding the NMA, one of the most profiting markets can be the spare parts selling and maintenance of these aircraft.

13.2.9.2 SWOT analysis for new MoM aircraft

In this section, an analysis of the framework of a potential new mid-size aircraft will be analysed. Using the environmental data collected in this study, PARE will develop an analysis of the Strengths, Weaknesses, Opportunities and Threats of Boeing's NMA. More specifically, the SWOT analysis offers a foundational assessment model that measures what the organization can or cannot do, and its potential opportunities and threats. A more detailed definition of the section of the SWOT analysis is discussed herein:

- Strengths: describe what the Boeing NMA excels and might separate it from the competence.
- Weaknesses: describe what could stop the company from performing at its maximum level.
- Opportunities: external factors that favour the launching of the aircraft.
- Threats: external factors that might harm the new product launch.

Figure 13.79 shows the strengths, weaknesses, opportunities and threats of a new MoM aircraft. The main opportunity is the medium-sized market, which is also diffuse since other product lines such as the A321LR or the B737 MAX10 can capture some percentage of the demand.

The main weakness is that it is a new program. New programs imply high development and engineering work. If engineering and development work is missed, then it means that the design is obsolete compared to the available technologies. That is, more or less, Boeing's intention with the new MoM. Using high-tech tools as in the B787 would mean really high development costs of the program. The demand is not as big as it is in the B787 sector and that risk would be unjustified in the case of the Middle of the Market.

Taken all these arguments, a SWOT analysis is performed hereafter.

Strengths

1. Experience
    - 1.1. **Boeing has been manufacturing airplanes since 1940.** The company has passed by several new program launching and has a wide board of experts within its team.
    - 1.2. **Lessons learned.** The B787 program launch brought many delays and high program costs that affected Boeing's reputation. The lessons learned from this program can be applied to new aircraft development.
2. Customer-oriented design

   2.1. Boeing has been working together with the potential clients to add the features they want to the new aircraft.
   2.2. After several years in the industry, Boeing has developed a wide vision of the market needs and knows how to interpret them. The launch of the 787 is an example of this, an aircraft that helped to open more than 180 new markets for the company.

Opportunities

1. Lack of similar products
   1.1. **The mid-sized B757 and B767 fleet are getting obsolete.** The main aircraft models covering this segment of the market are no longer in production but still being operated by a wide range of airlines. When the replacement time comes, this might lead to an important potential demand.
   1.2. **The gap between the incumbent models' line-up.** There is no manufacturer offering a similar product nowadays. The single-aisle models fall short of range and the wide-body aircraft are oversized for the objective mission of the NMA.

2. Growing demand
   2.1. **The estimated demand for the MoM sector is around 9000 aircraft for the next 20 years**. From those, the NMA could take a big portion if launched on time.
   2.2. **Low-cost expansion.** The liberalization of the medium and long-haul travel provides to the low-cost carriers the possibility to access new markets, and consequently, the demand will grow. The NMA design could fit the requirements of the LCCs to operate in this segment due to the better economics that it will offer.

Weaknesses

1. **High development costs**. A clean-sheet design is estimated to cost around 10-15 billion US$, a riskier option than a re-engined version of an incumbent model.
2. **Problems with engines' manufacturers.** It is uncertain if the engines manufacturers will provide with a new design within a reasonable timeframe for the new NMA. If a new engine model does not arrive or arrives too late could lead to leaving the NMA program launch.
3. **The recent loss of trust in the company from the customers.** The series of accidents that involved the Boeing 737 MAX aircraft and took place between October 2018 and March 2019 pushed Boeing under heavy pressure from the authorities and airlines. Many B737 orders were cancelled, and this could lead to less acceptance of the NMA.

Threats

1. **Airbus A321neo.** Although it is a very different concept, the Airbus proposal to compete with the NMA is already in the market. With the new variants, the LR and XLR versions, the A321neo could take a big portion of the NMA potential demand.
2. **Cannibalize the B787.** The Boeing 787 Dreamliner is nowadays operating a big number of the objective routes of the NMA. A misstep from the company could lead the NMA to cannibalize a big part of the sales of the Dreamliner.

3. **Timeframe.** With the old mid-range fleet of B757s and B767s reaching their retirement age, airlines need to replace these aircraft as soon as possible, and if the NMA option is not yet in service, they will consequently choose another option.

These conclusions are summarized in Figure 13.79.

Figure 13.79. SWOT analysis for the new MoM aircraft

13.2.10 Engines for the NMA

One of the factors that most can impact the timing of the Boeing MMA launch decision is the availability of a suitable engine [88]. The capacity and willingness of engine makers to produce the adequate engine in the correct time frame can become the main "pacing factor" in the 797 decision.

The new MMA will need a new next-generation ultra-efficient engine with a thrust of 18.2–22.7 ton-force (approximately 45,000 lb) [89].

The 797 selling case is primarily sustained on the basis of reductions in operating cost. Although Boeing could implement new technologies to reduce operating costs, it will rely heavily on the engine fuel burn efficiency. This appears to be a key driver in terms of timing, both for program launch and entry-into-service (EIS).

To meet the challenging 2025 EIS, the engine/s would have to be certified during 2024. That implies an imminent engine selection that would require Boeing's confidence in engine technology that exists today or is at least in an advanced testing stage.

Three companies: CFM International, a joint venture between General Electric and Safran, Pratt & Whitney and Rolls-Royce, are specified as applicants for the project to develop a new engine. The design and delivery capabilities of the engine for the NMA will be considered in this review.

However, engines manufacturers are suffering some reliability problems that bring doubts about whether engine makers will have the bandwidth to support a new programme with service entry in the 2025 timeframe. Rolls-Royce is dealing with turbine and fan blade problems on some Trent 1000s that are one of two engines that power the 787s. Pratt & Whitney's geared turbofan engines have suffered durability and other issues that have spoiled the service entry of the A320neo. The joint venture between Safran and General Electric has had several problems with its LEAP engines relate to the appearance of cracks in the low-pressure turbine section, which forced Boeing to halt test flights of its 737 MAX jets. Those problems have affected a portion of the fleets and manufacturers are dedicating substantial resources to solve these issues.

All these recent industrial problems among engine makers could lead Boeing to adopt a rationale strategic for the dual-source (that is, offering airlines a choice of two engines) in order to mitigate the risk. However, both suppliers will have to share a market that is not so big, and the business case for those engines could become very thin unless they could also be mounted on other aircraft. If Airbus would decide to respond to the 797 with its own new MMA product, then it could use the same engines, perhaps enhancing the business case for more than one engine option.

Boeing is demanding an engine that burns 25% less fuel for every pound of thrust it produces compared to the 757's decades-old turbines. Up to now, Boeing has had discussions with 3 providers: CFM International, Pratt & Whitney, and Rolls-Royce. A call for proposals was launched at the end of 2018.

There is no obvious answer yet because the models available now are either too big or too small. But for Rolls-Royce in particular, the 797 is the next opportunity to participate in a major aircraft program that could be the first application for Rolls' Advance engines. For Pratt & Whitney, the 797 could be the platform for the next iteration of its geared turbofan (GTF); now powering the A320neo and Bombardier C Series, and it would be a step ahead of putting a GTF on a true long-haul aircraft.

To answer the key questions about the engines for the new MMA, we have performed 3 technical assessment covering the following items:

- The roadmap for engines fuel efficiency.
- The current problem of the engine manufacturers.
- Feasibility of a fuel-efficient new engine for the MMA

As the deep technical level of the first two ones exceeds the purpose of this chapter, the whole corpus of these two analyses is presented in the Annexes at the end of the document.

Additionally, one of the originals research questions of the study was to analyse if the development of new engines for the MMA could help to revive the A380 to compete with modern long-range twins. To that aim, we have performed a trade-off analysis of possible engines for the A380. However, considering the announcement made by Airbus on February 2019 in which it declared to officially end the A380 program, this analysis is not part of the core of the study, although it can be consulted as part of the Annexes.

13.2.10.1 Assessment of the possibility of developing a new engine for the MMA

In this section, we perform a technical analysis of technologies available, the possible directions for engine improvements and the feasibility of each one of the candidate companies to develop the product required by the new MMA.

While maintaining the direction of engine improvement in order to increase cycle parameters and the bypass ratio, it is expected to pay more attention to research of power plants (PP) of non-traditional layout design: propfan engines ("open rotor") with bi-rotating propfans (PF); engines of complex thermodynamic cycles (with intermediate air cooling in the process of compression and heat recovery in the process of gas expansion in the turbine as well as engines with detonation combustion).

The key role is played by:

- light compact heat exchangers, coolers, etc…
- distributed PP (driving several propulsion fans from one power generator), deeply integrated with the airframe elements and allowing for bypass ratio increase without increasing the diameter of the PP
- hybrid PP, driving the fans simultaneously from the turbines and electric motors.

On the one hand, the transition to such layouts can potentially provide a significant improvement in the engineering and economic characteristics of the aircraft, and, on the other hand, it is associated with apparent risks due to the limited experience in the creation of such power plants. The transition to such configurations in practice is a key step and requires significant material costs and time. Taking into account the expected commissioning date of the aircraft under the NMA program, it can be affirmed that there will be no significant changes in the engine's configuration. Current engines will be taken as a baseline when designing a new engine.

Engine options

The main feature of the requirements for the NMA future engine is a thrust of about 18 tons. Since the completion of the PW2000 / F117 program and the termination of the Boeing C-17 military transport aircraft production, this level of thrust has not been included in programs of western engine manufacturers. This range is higher than the capabilities of new engines, such as the CFM Leap or Pratt & Whitney PW1000, but lower than the larger turbofan engines such as the Rolls-Royce Trent or General Electric GEnx. It should also be noted that Boeing must convince engine designers of the NMA program potential since companies must be interested in winning the competition for making a profit. Since the aircraft is commercial, it must rely on innovation, and at the same time on well-developed and proven technical decisions. This suggests that the new engine will be developed on the basis of current engines.

The most awaited engine options from various manufacturers are:

- GE engine on the basis of GEnx (GE9X);
- CFM International engine on the basis of Leap;

- P&W engine on the basis of Pure Power PW1100G;
- Rolls Royce engine on the basis of Trent 1000 or Trent XWB.

At this moment, Rolls-Royce has problems with its Trent 1000 program and it is embarking on a major restructuring; Pratt & Whitney is straining to keep up with Airbus production ramp-ups following the problematic introduction of its PW1100G on the A320neo [90]. Therefore, one of the determining factors in designing an advanced engine for NMA will be the availability of technologies that will allow achieving the necessary reduction in fuel consumption. In addition, it is important to note the production capabilities and the elimination of possible shortcomings. These factors determine the timeframe for the creation and commissioning of new products. The possibility of new technological decisions commissioning is conveniently assessed on the scale of technology readiness level (TRL) adopted by NASA and shown graphically in Figure 13.80. To assess the possibility of engine design in a given time with a 25% reduction in specific fuel consumption relative to current long-haul aircraft engines, we use the data presented in [91]. Figure 13.81 shows the time dependence for a new technology commissioning based on the technology readiness level (TRL).

To assess the possible gain in reducing fuel consumption, we also use the data given in [92] and presented in *Table 13.24*.

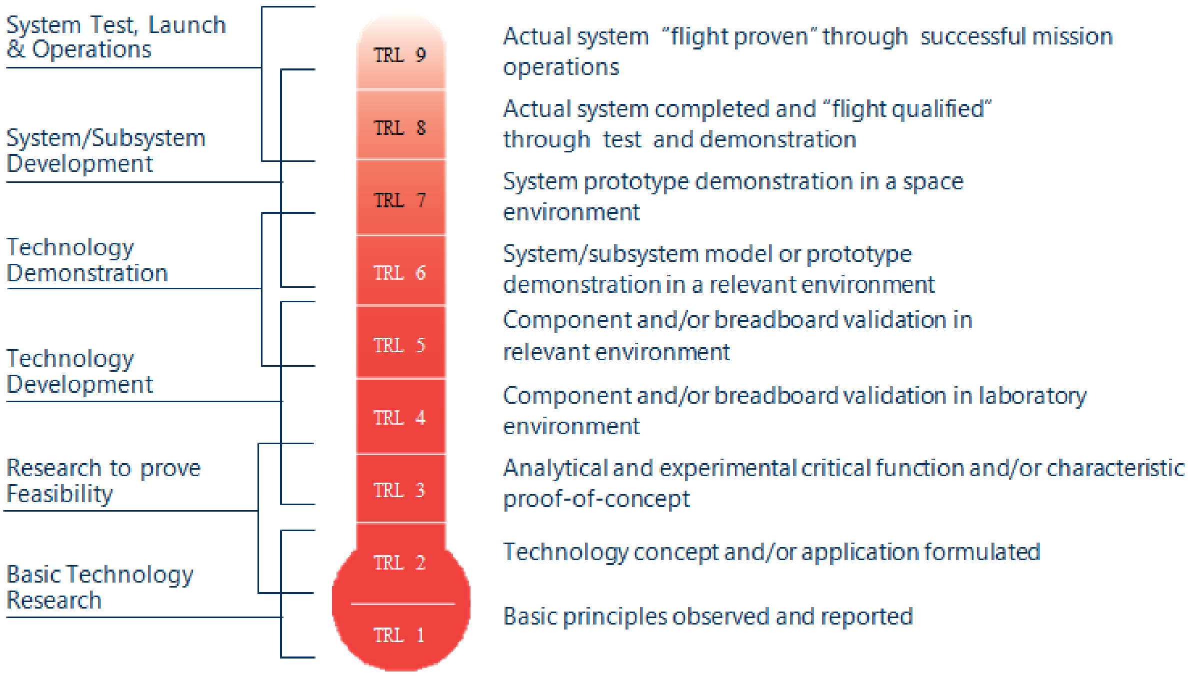


Figure 13.80. Technology readiness level on NASA's scale [92]

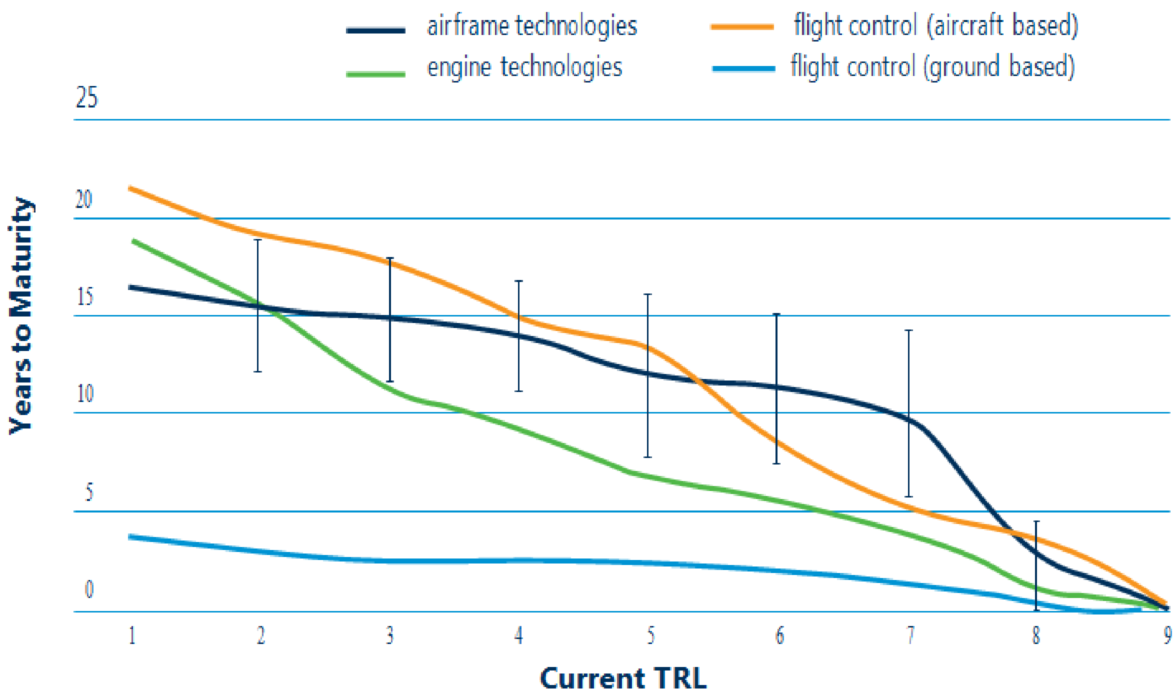


Figure 13.81. Maturation Timeline for Technology Readiness Level [92]

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current TRL	Availability of technology (calculated)
New engine architecture	Geared Turbofan		before	10 to 15%	7	2016
	Advanced Turbofan		before 2020	10 to 15%	7	2016
	Counter Rotating fan		after 2020	15 to 20%	3	2023
	open Rotor/Unducted fan		after 2020	15 to 20%	5	2019
	New engine core concepts (2nd GeN)		after 2030	25 to 30%	2	2026
	embedded distributed Multi-fan (2nd GeN System)		after 2030	< 1%	2	2026
Advanced engine Concepts	fan	Component Improvements	before 2020	2 to 6%	8	2013
		Zero Hub fan	before 2020	2 to 4%	7	2016
		Very High BPR fan	before 2020	2 to 6%	7	2016
		Variable fan Nozzle	after 2020	1 to 2%	7	2016

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current TRL	Availability of technology (calculated)
	Combustor	Variable flow Splits	after 2020	1 to 2%	5	2020
		Ultra-compact low-emission combustor	after 2020	1 to 2%	5	2020
		Advanced Combustor	before 2020	5 to 10%	8	2013
	Compressor	Bling-concept	after 2030	1 to 3%	3	2023
		Blisk-concept	after 2020	1 to 3%	7	2016
	Variable Geometry Chevron		after 2020	< 1%	5	2020
Nacelles and Installation	Buried engines		after 2020	1 to 3%	5	2020
	Reduced nacelle weight		before 2020	1 to 3%	7	2016
engine Cycles	Adaptive Cycles		after 2030	5 to 15%	2	2030
	Pulse detonation		after 2030	5 to 15%	2	2030
	Boundary Layer Ingestion Inlet		after 2020	1 to 3%	3	2023
	Ubiquitous composites (2nd		after 2020	10 to 15%	3	2023
	Adaptive/Active flow control		after 2020	10 to 20%	2	2026

Table 13.24. Advanced engine technologies and expected date of commissioning

Analysing the statements and reports of the companies, comparing them with time dependencies and possible gains in reducing fuel consumption shown in Figure 13.81, it is possible to assess in a qualitative manner the possibility of designing an engine with a 25% reduction in fuel consumption, indicating roughly the commissioning date of a new engine for the NMA. It should be noted, that this study does not take into account the financial, production and other components of the process of an aircraft engine design, although they can have a significant impact at any stage of the life cycle of NMA power plant.

Analysing the data presented in *Table 13.24*, we can conclude that, back in 2013, engine prototypes with technologies that can significantly reduce the specific fuel consumption were tested, namely geared turbofan and high bypass ratio engine. An example of a geared turbofan is Pure Power PW1000G. In turn, the high bypass ratio engine is GE9X, which is passing flight tests [93], confirming the timeframes for different TRL shown in Figure 13.81. However, since these engines are not suitable in terms of thrust, the decisions worked out on these engines are not quite applicable to the required engine for the NMA, but they will most likely become the basis for making further decisions.

It is necessary to point out possible directions for the development of power plants in terms of their application in the Boeing NMA. This is due to the relative unavailability of complete information concerning the work of engine manufacturers. That makes sense since it is commercially confidential, and its distribution can harm the companies. Development directions are shown in *Table 13.25*.

Development directions	Technologies	TRL
In terms of thermogasdynamic processes		
Increasing fuel efficiency of engines for long-haul civil aviation aircraft	High-performance thermodynamic schemes of advanced engines for long-haul aircraft	4–6
	Model heat exchangers, coolers and regenerators, samples of advanced cooling systems for the engine hot section	5
	The concept of ultra-high bypass ratio turbofan	6–7
A decrease in specific weight, volume and overall dimensions of engines	Engine configuration with increased specific thrust and extensive use of composite materials	5–6
Improving the integration of the power plant and airframe	The layout of the engine nacelle, pylon and wing with minimal noise	6–8
	The layout of the power plant and the airframe with common structural elements	5
Effective modelling of gas-dynamic processes in engine elements Optimization of gas-dynamic characteristics of the elements of engine and power plants Optimal blading of impeller machines	Low-noise, high-performance fan and LPC with swept and inclined stator and rotor blades	6–7
	Fan with ultra-low tip speed at the periphery and a geared drive	6
	Efficient high-load turbine	6
Transient processes in the elements of the engine airflow duct. Transient processes in impeller machines. Ways and means of reducing losses and increasing stall margins	Numerical methods for studying transient and stall processes in ducts, compressors and turbines.	
	Methods for diagnosing transient processes in impeller machines	
	Active methods for controlling flow ducts, compressors and turbines (MEMS technologies, barrier and corona effects, microwave plasma).	6–7
	Active methods for increasing the stall margins.	7
	Superggressive transition ducts of GTE with a flow control system	5
	The design of spray units to operate with fuels of different fraction composition	5

Development directions	Technologies	TRL
Creation of methods and means for increasing the efficiency of mixing and combustion processes. Creation of methods and algorithms for modelling the processes of the air-fuel mixture. Creation of physicochemical and mathematical models and methods for calculating the main characteristics of the processes in various combustors	Method of organizing work process in the main combustor at low excess air factors and high gas temperatures (near-stoichiometric combustion with T>2000 K)	
	New highly efficient fuel burning schemes.	
	New designs of gas turbine power plants combustors	6
	New algorithms and methods for numerical modelling of high-temperature reactive flows using high-performance computing technologies	
In terms of strength		
Development of technologies for ensuring strength reliability	Blisks with blades made of new super heat-resistant alloys and disk parts made of the new disk heat-resistant alloys	7
	Innovative technologies for the manufacture of parts and components of advanced gas turbine engines made of next-generation nanostructured, ceramic and composite materials	5–6
	Antifriction nanostructured ceramic and composite materials and coatings for friction type bearings, front and rear bearing supports of the high- and low-pressure compressor rotor with segmental friction type bearings	4–6
	Experimental fan gearbox of advanced turbofan	6–7
In terms of power plant control system		
Development of aircraft power plant automatic control theory	Development of methods for mathematical modelling of aircraft power plants and their automatic control systems. Improved methods for controlling aircraft power plants. Methods for optimizing the laws and algorithms of power plant control.	
	Intelligent assemblies of GTE, circuit design, design definition	7
	System architecture and control algorithms of intelligent assemblies	7
	Electronic control with a built-in mathematical model of high-level GTE	6

Table 13.25. The table shows the main directions of engine manufacturers' research in terms of engines application until 2025

It is necessary to take into account that the directions of research indicated in this table and their technology readiness level are different for each company as well as application options. This fact will ultimately influence their application on advanced engines.

13.2.10.2 Rolls-Royce

Rolls-Royce is considering to connect its program with an advanced engine for the NMA [94]. As reported, the result of the UltraFan program should be an engine with a 25% fuel efficiency improvement relative to the Trent 700 with entry into service in 2025. The engine should be based on a universal gas generator, developed under the Advance program, using advanced production technologies, including 3D printing, welded assembly and highly productive thermoplastic materials. As part of the UltraFan program, a fan drive is actively developed, which should significantly increase the fuel economy. The two-stage evolution of today's Trent XWB (Figure 13.82) underlies the company's idea. It provides the basis for the first Advance engine, which will have a bypass ratio of over 11 and overall pressure ratio of more than 60. In turn, it is expected that the UltraFan engine will have a bypass ratio of about 15 and an overall pressure ratio of about 70 [95].

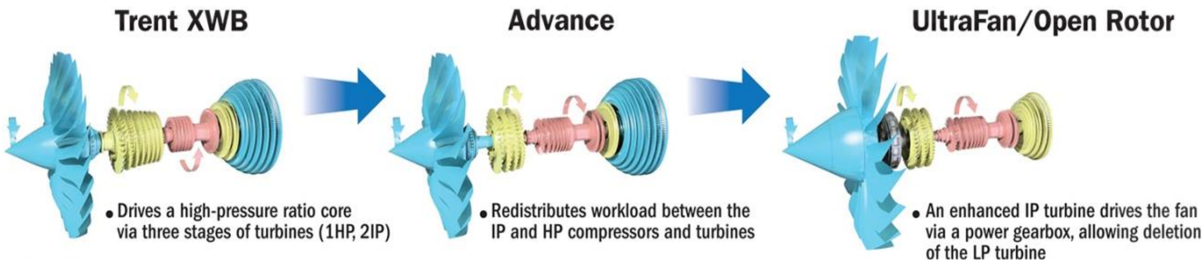


Figure 13.82. Evolution of the Trent XWB into the UltraFan [96]

The elements of engine units are developed under the programs that are connected with the European Union and national programs (Figure 13.83).

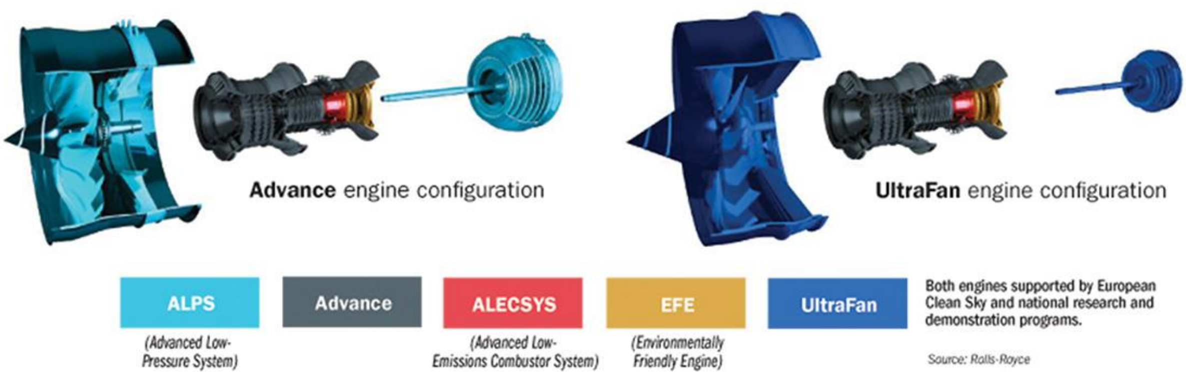


Figure 13.83. The connection between Advance and UltraFan development programs [96]

Since the Advance and UltraFan programs are interrelated (Figure 13.84), there is a good reason to consider the technologies used in both programs.

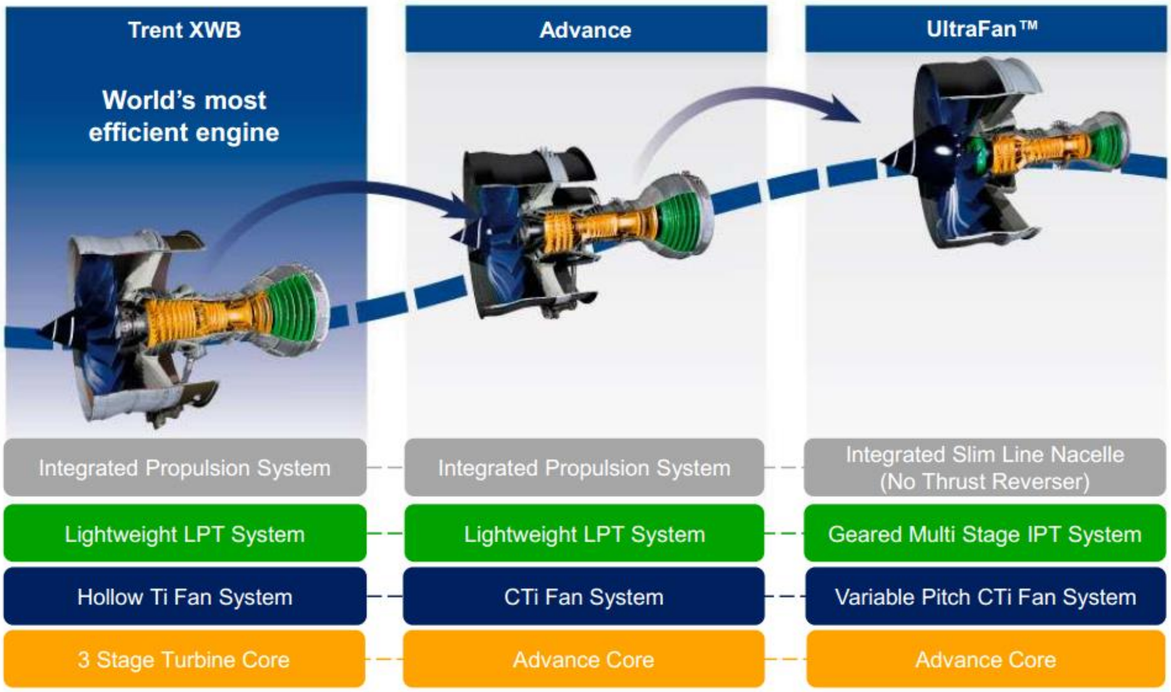


Figure 13.84. Advance and UltraFan technology development [96]

The new Rolls engine will have a relatively larger high-pressure compressor with up to 10 stages (compared to six on the Trent XWB) and a greater pressure ratio, and it will be driven by a two-stage turbine against the single-stage used today. At the same time, the IP compressor will shrink from the eight stages of today's XWB to around four, while the IP turbine count will be cut to one from two stages. The new configuration provides a very lightly loaded high-pressure spool, which gives good efficiency and, more importantly, significant commonality with the follow-on core of the UltraFan [97].

In addition to the advanced engine architecture use, Rolls Royce uses new materials in advanced engines, which will improve engine weight. The blades and fan casing are made of lightweight CTi. Advanced CMCs and Ni alloys are used in the turbine. The technology of additive manufacture is widely used in engine production, allowing obtaining previously unavailable shapes and configurations of engine structural elements. These technologies, as well as technologies developed under the programs that are funded by the UK government and the European Commission, will provide the necessary technical background for the creation of UltraFan. Engine development programs, which will support the UltraFan program, including [98]:

- CEMTEC – The development of Silicon Carbide-based Ceramic Matrix Composite technologies for future engine architectures, helping to reduce fuel consumption through reduced component weight while also improving cyclic life and reducing manufacturing lead times.
- CHASM – The design, integration and manufacture of new technologies to support the development of a power gearbox.
- IPCRESS – The development of an intermediate pressure compressor which is integrated with the UltraFan power gearbox.

- SUSSUDIO – A Rolls-Royce led project to develop the detailed design of an ultra-high bypass ratio gas turbine engine demonstrator.

As a result of the implementation of these programs, the UltraFan engine family will get the technologies specified in Figure 13.85.

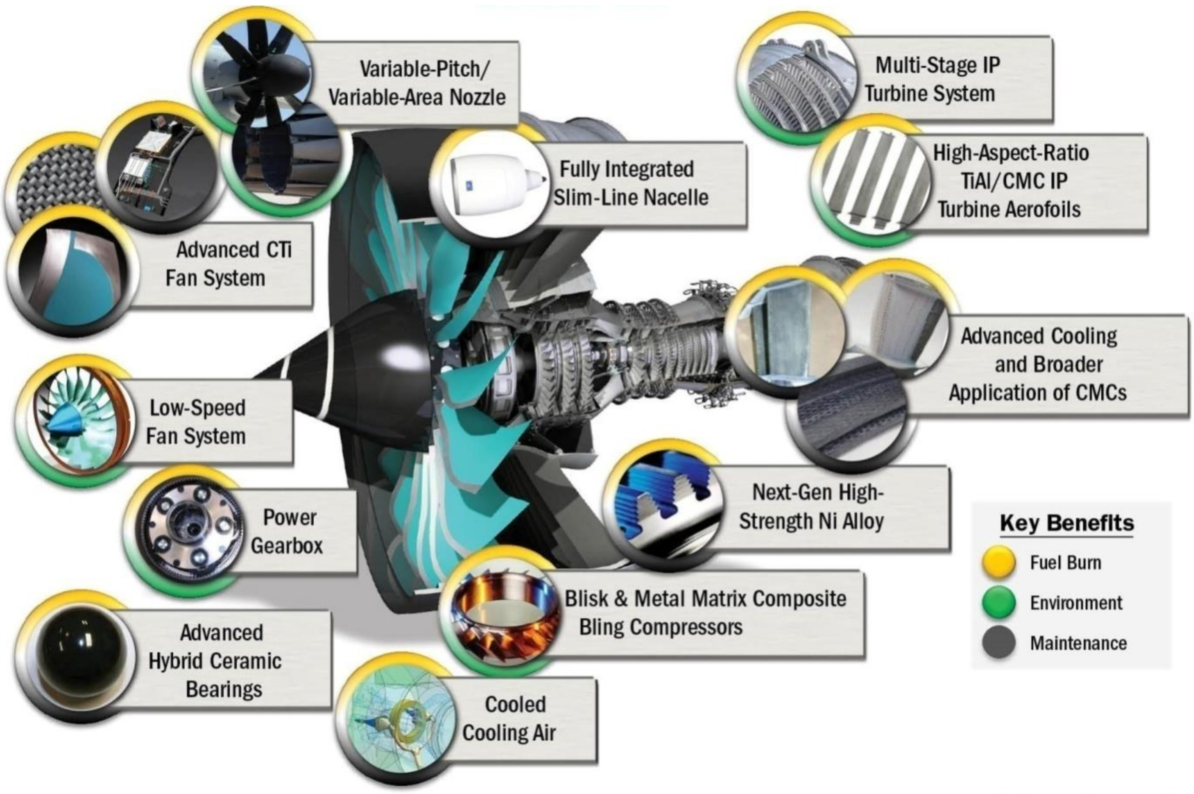


Figure 13.85. Technologies used to create UltraFan

The key difference between the UltraFan and the Advance family is the transition to a two-shaft engine architecture with a geared fan. The statement about the variable pitch fan blades is also significant (Figure 13.86). This will have a positive effect on the engine's efficiency since it will provide an additional control factor in the automatic engine control system. This, in turn, will provide an opportunity to ensure the engine operation at optimum thrust ratings under various flight conditions. At the same time, this system requires a complex drive mechanism for turning the fan blades. Under the conditions of reducing the size of the engine gas flow duct, this is an extremely difficult task, which will require additional costs for research and testing of demonstrators.

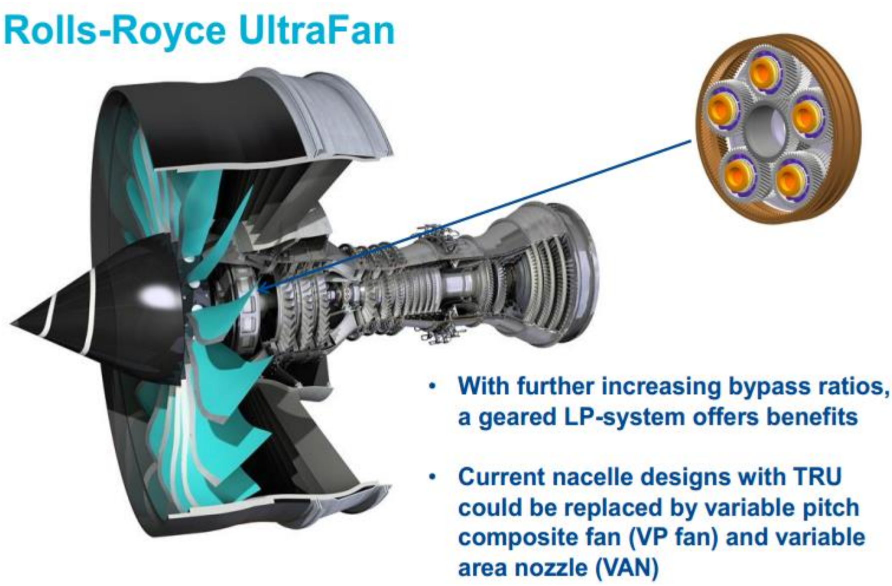


Figure 13.86. Position of the fan drive gearbox in the engine

One of the key elements that make a decisive contribution in ensuring the necessary fuel efficiency of the engine is the use of a low-speed geared fan (Power Gearbox). Tests of the first power gearbox demonstrator began on a specially designed installation in 2017 [99]. In other words, in the middle of 2017, the level of TRL 6 was reached. This suggests that by 2022 it will be possible to put a similar fan into service. But this is only one of the systems. It is also necessary to note that it was planned to test the Power Gearbox during 2015 [100]. There may be other delays that are not indicated in the publications.

Thus, Advance is known to be developed as an independent engine family and is also a starting point for UltraFan. Rolls-Royce plans to carry out ground tests of the UltraFan demonstrator in 2021 and the replacement of engines on the A350 aircraft in 2025 [101]. More detailed achievements of the company in the direction of Advance and UltraFan are specified in [89]. The Advance demonstrator full power test is also important [102], as it makes possible to evaluate the readiness of the engine for TRL 6. Commissioning date from the current TRL is about 5 years.

Based on the publications previously considered, taking into account the data presented in Figure 13.87 and the technologies that will be used in the Advance and UltraFan engines, it can be assumed that by 2025 it is possible to start deliveries. At the same time, a possible fuel efficiency improvement can vary from 15 to 29% versus the level of the Trent 700 family. The advanced program will also have a further impact on the commissioning date of the engine since the technical solutions that are not implemented in it will directly affect the UltraFan (Figure 13.87). A wide range of thrust scaling will allow Advance and UltraFan meeting the requirements for the Boeing NMA.

Technology EIS Readiness	2020+	2025+
Bypass Ratio	11+	15+
Overall Pressure Ratio	60+	70+
Efficiency relative to Trent 700	20%+	25%+

Figure 13.87. Comparison of modern Rolls-Royce engines with Advance and UltraFan.

13.2.10.3 CFM International

Other companies that are planning to take part in the competition are GE and CFM International. Company data can be considered both together and separately. This is due to the fact that CFM is a joint venture of GE and French Safran, and also because the company's advanced products are interrelated. In order to maintain its position in the global market, CFM International, as well as the companies that formed it, is actively involved in new technology development programs. As shown in [103], the GE9X engine is built using proven Leap technology. CFM International will also take part in the competition, even if the engine thrust exceeds 50,000 lb [104], which has a significant impact since the upper limit of thrust for CFM was 50,000 lb. Taking this fact into account, it is possible to assume that the most likely scenario would be just a proposal of CFM International to participate in the tender for the supply of Boeing NMA propulsion engine. In this scenario, the company will have several directions for the development of the engine. The first is to scale the engine of the LEAP family in the direction of increasing the thrust to the required level, and the second is to scale the GE9X engine in the direction of reducing the thrust to the required level.

At the same time, LEAP is an earlier engine versus the GE9X, which is an advantage in choosing GE9X as the basis for the design. The intermediate engine between LEAP and GE9X is the GEnx engine, but LEAP has entered service earlier. It is especially necessary to take into account that GE9X is not in service. Scaling the engine in any direction can cause various difficulties associated with changing the geometry of the structure, so the direction to be chosen by the company is unknown.

Based on information from the source [105], CFM international will offer an engine on the basis of Leap with GEnx elements.

The baseline architecture of the LEAP engine is based on a smaller version of the Safran low-pressure turbine used in the GEnx engine. The LEAP engine, unlike its predecessor, the CFM56, is designed to operate at a higher pressure, which is partly the reason for its efficiency. However, to increase the service life of the engine, the designer plans to set the operating pressure below the maximum. However, it is worth suggesting that new materials will be applied, which will enable removing this restriction in the future engine for an aircraft created under the NMA program. Its reliability is also supported by the use of an oil cooling system based on gearbox, which is similar to the GEnx system, with coolers installed on the inner lining of the fan duct.

One of the first cases in the history of civil aviation is the use of 3D printed parts in engine design.

The LEAP engine shows a 16% reduction in fuel consumption compared to its predecessor, due to the use of blisk technology in the compressor, second-generation TAPS combustion chamber (TAPS II), ceramic matrix composites (CMC) for turbine casing and the bypass ratio of about 10-11. A 15% reduction in fuel consumption and CO_2 emissions versus current engines, a 50% cut in NOx emissions as well as compliance with the most stringent noise standards are also observed[106].

These performance advantages are based on proven Safran and General Electric engine technologies. These technologies include the use of 3D woven composite material for the fan case and blades, as well as advanced 3D aerodynamic design technique used for the blades of the low-pressure section, and new stronger, lighter alloys such as titanium aluminide (TiAl) and ML340 (very high-strength steel for high-temperature applications). The main technologies used in the engine are shown in Figure 13.88.

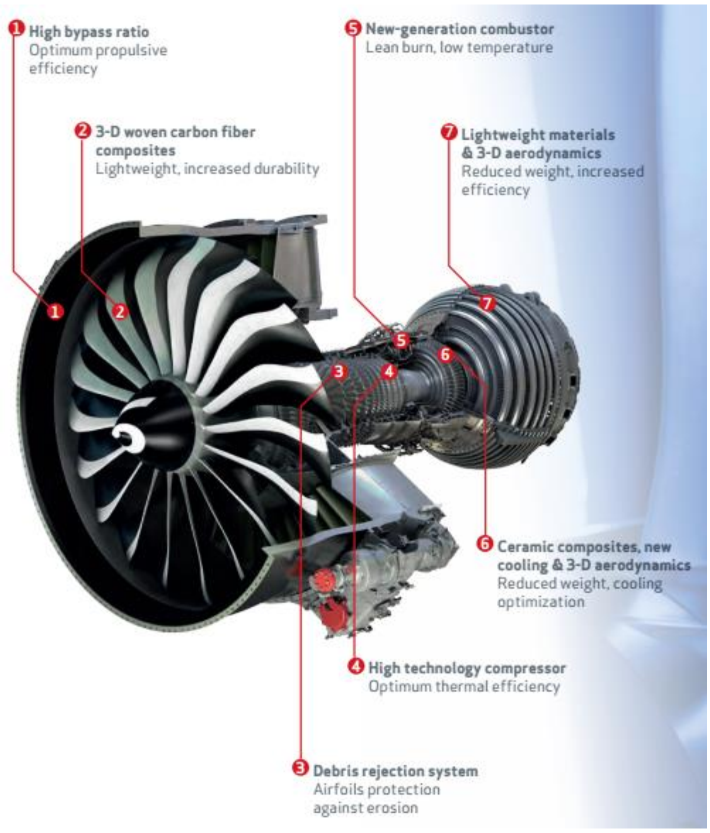


Figure 13.88. The main technologies used on the Leap-X engine

The main engine performances of the Leap-X family are presented in

Characteristics and parameters	LEAP-1A	LEAP-1B	LEAP-1C
Max. Take-off thrust (lbf)	35.000	28.000	31.000
Overall pressure ratio	40:1	40:1	40:1
Bypass ratio	11	9	11
Fan diameter (in)	78	69	77
Number of fan/low-pressure/high-pressure compressor stages	1+3+10	1+3+10	1+3+10
Number of high-pressure/low-pressure turbine stages	7+2	2+5	2+7
Entry into service	2016	2017	2018

Table 13.26.

Characteristics and parameters	LEAP-1A	LEAP-1B	LEAP-1C
Max. Take-off thrust (lbf)	35.000	28.000	31.000
Overall pressure ratio	40:1	40:1	40:1
Bypass ratio	11	9	11
Fan diameter (in)	78	69	77
Number of fan/low-pressure/high-pressure compressor stages	1+3+10	1+3+10	1+3+10
Number of high-pressure/low-pressure turbine stages	7+2	2+5	2+7
Entry into service	2016	2017	2018

Table 13.26. The main engine performances of the Leap-X family

Since the technologies used in GEnx became the basis for the further development of GE and CFM International products, we will not consider GEnx.

The remarkable thing is that the technical developments that will be successfully implemented on the newer GE9X will also appear on the proposed engine for the NMA. These include the GE9X fan blades, which are the next generation versus LEAP, the number of fan blades is reduced by 2 pieces compared to LEAP. According to [107], the specific fuel consumption has improved by 5% compared with any other current engine for wide-body aircraft, the bypass ratio is about 10, and the total pressure ratio reaches 60 (Figure 13.89). The engine features include new ceramic composite materials used in the manufacture of turbine blades, which significantly increase the temperature in the engine combustion chamber, 3D printing of complex parts that cannot be made using conventional means of materials machining, fourth-generation fan blades, etc.[108].

Analysis of materials and parameters of the cycle allows us to conclude that the GE9X engine has a relatively high thermodynamic perfection. In this case, it is advisable to take this engine as a baseline to create an engine for a new Boeing NMA. However, as previously stated, Boeing expects a 25% reduction in fuel consumption relative to current engines. The GE engine does not meet this requirement, which should lead to structural changes and improvements. With such high cycle parameters at this level of material development, it is difficult to implement a significant reduction in fuel consumption by a further increase in thermodynamic cycle parameters.

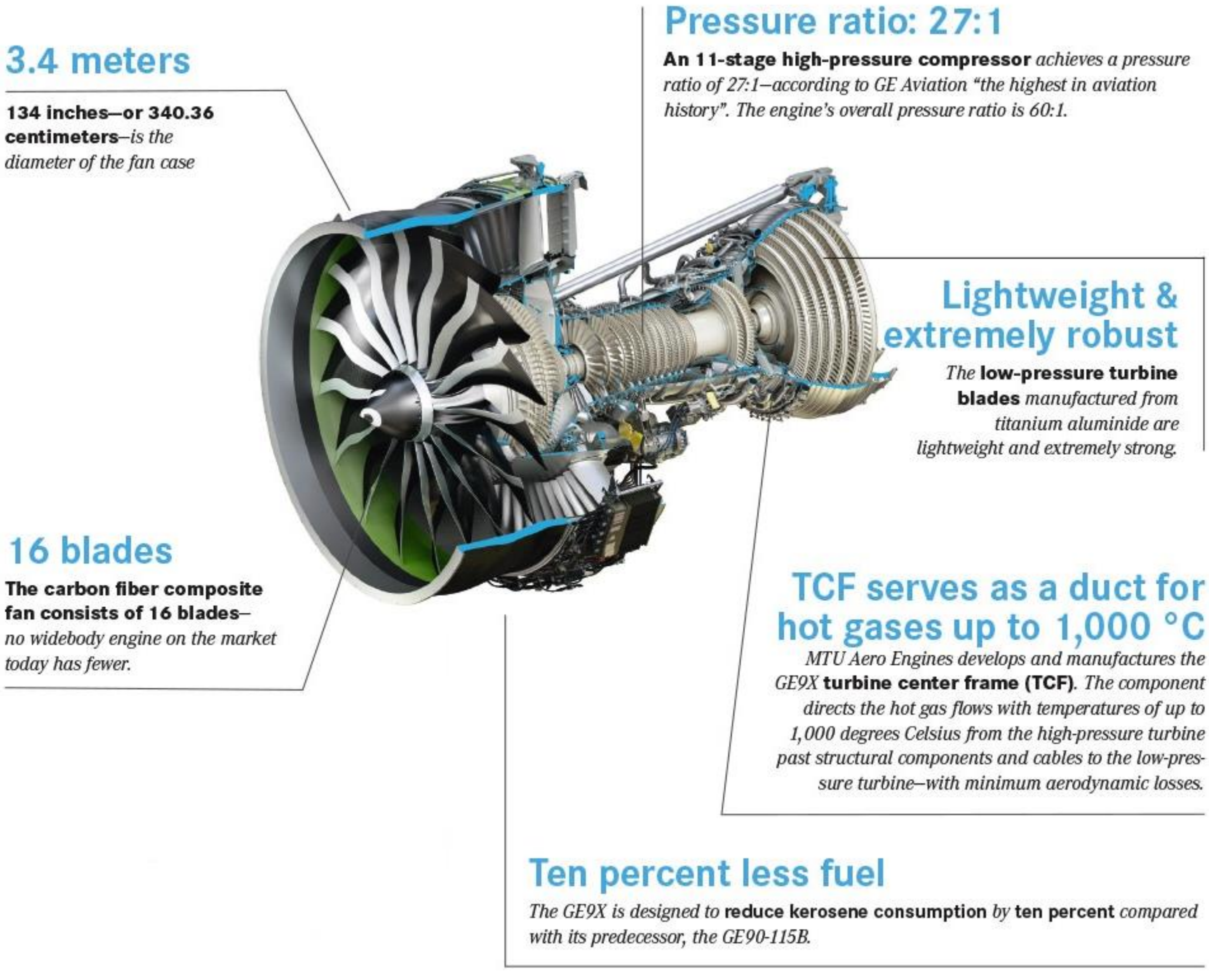


Figure 13.89. Specific features of the GE9X engine

According to [109], CFM International examines any and all necessary engine structures, including the geared fan. This trend with increasing bypass ratio can give the necessary improvement in fuel efficiency. The company has exploratory studies on reduction gear within the Quiet Clean Short-Haul Experimental Engine (QCSEE) program[110], which will allow the company to avoid lawsuits from Pratt & Whitney. The QCSEE reduction gear is shown in Figure 13.90.

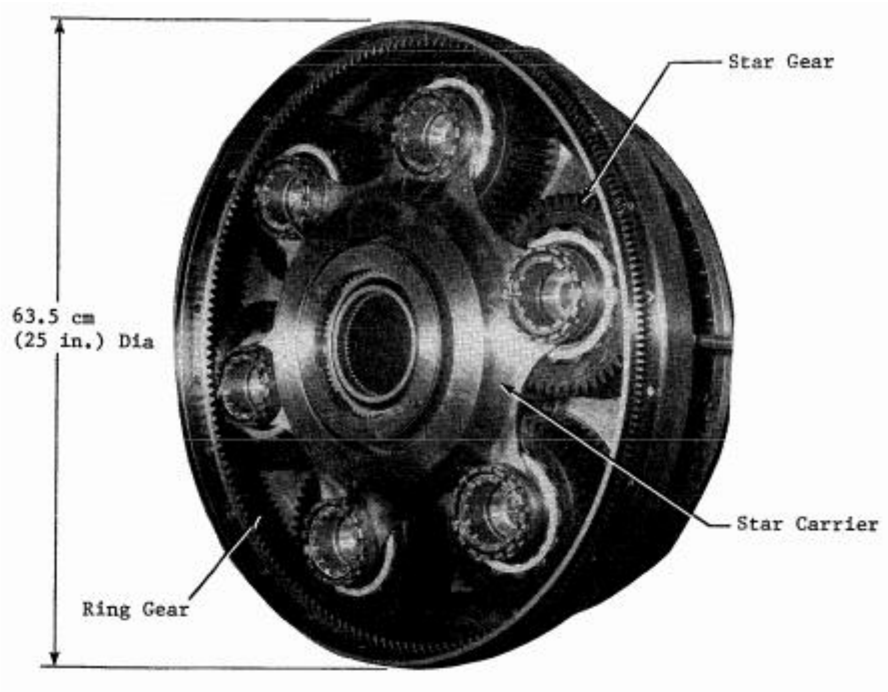


Figure 13.90. QCSEE UTW Main Reduction Gear [110]

Taking into account the levels of TRL presented in Figure 13.81 and the expected improvement in fuel efficiency shown in *Table 13.24*, we can conclude that CFM International can achieve the required fuel consumption values required for Boeing NMA.

13.2.10.4 Pratt & Whitney

Pratt & Whitney was one of the first to confirm that it considers enlarged versions of the PW1000G engine family in the context of an application for the Boeing NMA [111]. The company participates in the Federal Aviation Administration (FAA) Continuous Lower Energy, Emissions and Noise (CLEEN II) initiative [112], under which the advanced technologies applicable to Pure Power Geared Turbofan (GTF) with ultra-high bypass ratio will be developed. The work aims to improve the thermodynamic efficiency, in particular in the gas generator. The company is also actively working on the development of the engine nacelle to ensure a reduction in fuel consumption and noise level. In the direction of engine nacelle development, the company works with NASA, as part of NASA's Ultra-High Bypass Advanced Nacelle Technologies Flight Demonstration program. The goal of this program is to improve engines for commercial aircraft, reduce environmental pollution and increase fuel efficiency. A significant advantage of PW is that the company has a geared turbofan and has experience in operating this system. The schematic diagram of the PW 1100G-JM in comparison with the engine of the traditional scheme is presented in Figure 13.91. As can be seen from the presented scheme in Figure 13.91, the reduction gear allows reducing the number of low-pressure turbine stages. This results in weight reduction and lower operating costs. The main technical solutions used in the PW 1100G engine are shown in Figure 13.92.

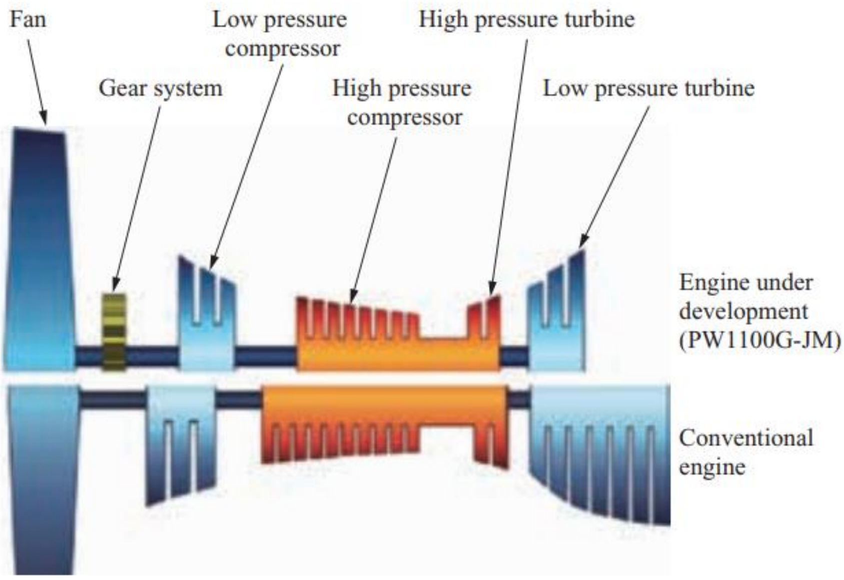


Figure 13.91. Comparison of the geared turbofan and the traditional scheme

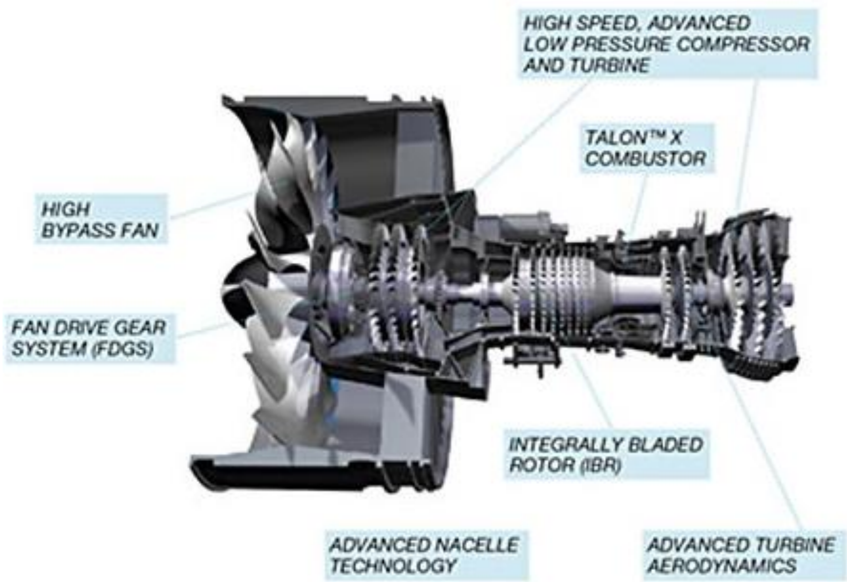


Figure 13.92. Fundamental technology of PW1100G

It should be noted that the company has achieved a significant reduction in noise level and fuel consumption of the engine and continues to work in this direction. Also, as follows from [113], PW is working on an engine with an increased bypass ratio and the ability to transfer large forces through the fan gearbox.

Based on the mentioned above, it can be assumed that the company will offer a high-bypass ratio engine with a well-proven geared fan system and an advanced nacelle for the Boeing NMA. Considering these solutions in accordance with the table of the expected reduction in fuel consumption, it is possible to assume that PW will be able to develop an engine with the required fuel consumption. It is necessary to pay attention to the possibility of increasing the parameters of the operating cycle, which will also bring a reduction in specific fuel consumption.

13.2.10.5 Conclusions

Based on the literature analysis and the development directions of aviation gas turbine engines, it is possible to draw the following conclusions:

1. The reviewed companies have the technology and potential to develop a new engine for the Boeing NMA within a specified timeframe, which makes the choice of a future engine supplier unclear. At the same time, companies must be confident about the success of future aircraft. This confidence will be determined by the rightness of the Boeing strategy selection and the forecast of the future passenger transportation market.
2. Since the commissioning date of a new aircraft is scheduled for 2025, the possibilities of engine manufacturers to create and develop fundamentally new engine architectures are limited. In this aspect, the use of current gas generators (cores) of the engine with their subsequent improvement, as a thermodynamic machine, is most appropriated. However, achieving the necessary reduction in fuel consumption in this way can be difficult and costly. It is possible to achieve a significant increase in fuel efficiency by a combined method, namely by an increase of bypass ratio, the use of a geared fan and an increase in engine operating cycle parameters.
3. All three considered companies use similar directions to improve power plants based on improving the aerodynamics of the air-gas channel of the engine and its nacelle, the use of ceramic composite materials for combustion chambers and turbines as well as the use of new alloys for compressors and other engine elements. This is determined by the desire of improving the weight perfection of the engine, increasing the parameters of the operating cycle and reducing losses in the engine, among others. A significant difference is the use of a geared fan in the PW 1000G engine family. The company gets an operating experience of such systems and the ability to foresee and eliminate possible problems when creating a larger engine for the Boeing NMA aircraft. This aspect may be one of the key factors that will affect the choice of an engine supplier for future aircraft.
4. The additive manufacture technology (3d printing) will most likely become a significant production factor that may affect the commissioning date of a new engine. The potential of this factor is not yet fully appreciated. The desire of companies to increase the number and range of manufactured parts using 3D printing indicates the possibility of a significant increase in production rate. How this will affect the commissioning date of a new engine is not reliably known.
5. Considering that Rolls-Royce refused to bid for engines for the Boeing NMA [105], because of the failure to meet the lead time of the engine, it can be assumed that the main participants will be CFM International and Pratt & Whitney. By some estimates, companies will be able to supply engines until 2025-2026. At the same time, it is necessary to expect from Rolls-Royce to offer new options for engines with the considered technologies. In the case of a launch postponement of the Boeing NMA program at a later date, the company will be able to offer the necessary engines.

13.2.11 New Boeing MMA

One of the main questions raised in recent years in commercial aircraft manufacturing has been whether Boeing will finally launch a new mid-sized airplane to address the so-called Middle of the Market (MoM). According to Boeing, this new aircraft, known as B797, would cover the market between aircraft 737 and 787, a mid-range market in high demand for the boom of transatlantic flights, coast-to-coast flights in the United States, as well as the Asian market.

The development of a new mid-range aircraft concept will allow Boeing to compete with Airbus products. The increasing sales of the A321neo are allowing Airbus to capture the mid-range market, surpassing the sales of the largest variants of the Boeing 737 MAX, known as the MAX 8 and MAX 10.

The problem for Boeing is that the A321neo is a fundamentally stronger aircraft, both in terms of operating and unit costs (excluding pricing), and in terms of operating performance on metrics like payload and range. Therefore, Boeing needs an offering in the MoM space, or it will miss out on thousands of new jet sales over the next 20 years in this market segment.

However, there is still much uncertainty about the design of the B797. Boeing is planning two versions of the new aircraft. On the one hand, a version called 797-6X with capacity for 220 passengers and a range of 5,000 nautical miles, which would enter into the market in 2025. On the other hand, a second version denominated 797-7X that can accommodate around 280 passengers and offer 4,500 nm of range, which would see the light two years later[114].

With the new middle of the market airplane, Boeing pursues a set of objectives: i) open new and profitable markets, ii) enable new business models, iii) increase profits on existing routes, iv) restructure networks for better-operating efficiency and v) reduce turn time-increase aircraft utilization.

The 797 looks like a good option for Boeing, considering the growing interest from airlines for a new midsize plane. There is still a tangible 757 and 767 replacement market that this aircraft would be perfect for, covering customers like Japan's All Nippon Airlines (for whom the 787-8 is overkill on intra-Asia routes) and Delta Air Lines (who would fly the MoM to Europe and Latin America replacing 767's and A330-200s).

The 797 could even replace the A330-300 on certain routes in East Asia, and more importantly, opening up all kinds of new markets. The Asia-Pacific region supposes a great market opportunity due to the growth expected over the next 15-20 years. Therefore, the goal will be to serve both heavily congested short-range flights within China and Asia as well as longer routes from, for example, the U.S. Midwest to central Europe far more efficiently than current generations of Airbus A330 and Boeing 767 jetliners.

The new Boeing aircraft development program is still very much in its infancy and, for that reason, it is slated to arrive in 2024-2025.

13.2.11.1 Boeing options for a new aircraft design

The 797 is considered the most critical launching decision of an aircraft in Boeing's history. Unlikely it will make technological leaps with the new aircraft since there will be a significant part of technologies from previous programs that can be reused. One of the problems is that the new wide-body aircraft will be designed to replace some narrow-body aircraft so that it has to offer similar operative costs and a competitive price. Obviously, the price has to be higher but not as high as the wide-body long-haul aircraft like the 787 (listed at US$ 280 million). Price is mostly driven by production costs, and for a wide-body aircraft, this makes the business case harder. Boeing's challenges within this aircraft are focused on manufacturing technologies, more than on design innovation.

In this section, the problems identified by several analysts within the NMA case are compiled, offering a comprehensive view of the main factors that affect the launch decision. Additionally, some features of the possible design, as well as the key technologies, will be discussed, after analysing several surveys made to airlines. Finally, the design trade-offs will be discussed.

The problems in the 797 case

Boeing faces three big challenges regarding the 797 development [115]:

Supply chain: Boeing must get its supply chain aligned with a price that customers are willing to pay. Analysts suggest that a competitive price would be roughly $76 million per airplane, making a list price somewhere between $130 and $150 million. That would be cheaper than the 787 Dreamliner (listed at $239 to $281 million) and the competing Airbus A330 ($238,5 million).

Development costs: Boeing estimates a market for the jet of between 2,000 and 4,000 airplanes. Some analysts have predicted that the development of the new Boeing 797 jet will cost between $15 billion and $20 billion, while other analysts think that an ideal budget would be 13,5$ billion. Besides, it is estimated that Boeing will need to sell between 1,045 and 1,585 aircraft units so that the new model is profitable. Higher development costs or lower than expected jet sales could reduce or eliminate profits on the 797.

Engines: as discussed in 0.2.10, engines represent a key factor for the new Boeing 797, since it can delay the program due to the inability to get a commitment for engines with as much fuel efficiency improvements as Boeing requested.

Another problem to be considered is the uncertainty in the demand forecast of the 797. This aircraft will replace Boeing's B757 and B767 aged as well as Airbus A330 and A321. However, much of the demand will deviate from B737 and A320 individual aisles to B787-8 and A330neo. Therefore, it is difficult to predict the demand and this lack of certainty limits the willingness of the engine manufacturer to take risks with new engines.

797 design and key technologies

The jet-to-be-launched 797 is slated to arrive in 2025. First with the base model, the 797-6X (220 passengers at 5,000nm) and the 797-7X (280 passengers at 4,500nm) two years later, according to Boeing's planning (Figure 13.93) [114].

Figure 13.93. Boeing 797-6X concept design.

In the early iteration of the 797-design, there are elements adapted from existing aircraft: a 737 Max-style tail cone, larger 787/777X sized cabin windows, and a 757/767/777-style windscreen. The door arrangement matches that of Boeing 767-200, very strongly suggesting a twin-aisle design. In relation to engines, Boeing's work is focused on a shorter inlet design to increase fuel efficiency.

Besides, the preliminary design suggests an ovoid hybrid design for the fuselage. The aim of such a design is to maximize the passenger space in the cabin, notionally a seven-abreast 2-3-2 twin-aisle economy arrangement. This represents one of the 797 main advantages over the A321, that is, the space to incorporate a business class with fully flatbeds. The ovoid shape of the fuselage would allow gaining width, which would give the margin to expand space for comfortable business. This design would solve one of the main points against the A321, which is not related to its operating capability, but with comfort on board.

In addition, according to the Paris Air show celebrated in 2017, the incorporation of modern technologies in the new aircraft model will be a key aspect (Figure 13.94) [116].

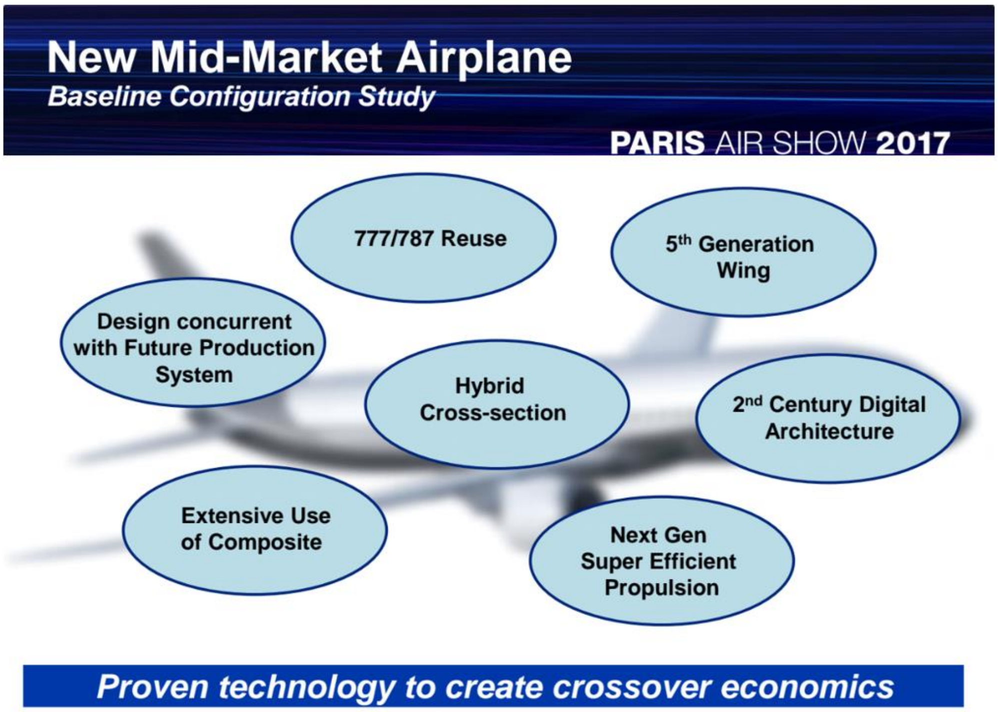


Figure 13.94. Boeing 797 technologies. Sources: Boeing, Aviation Week.

However, the 797 aircraft program is in an initial phase of development, more specifically in the design concept stage, therefore, it is very unlikely that first images of design resemble the final product.

Design trade-offs.

As the new Boeing 797 is in an initial phase of development, specifically in the concept design stage, there are several factors that Boeing may consider, and which could affect the final design features. These driving factors are discussed in this section.

In the first place, a characteristic that Boeing may need to consider is the size of the cargo hold. The big three U.S. carriers and their counterparts across the Pacific have very different views on how much baggage and freight the airliners should haul. While the large U.S carriers indicate that belly cargo is not a priority, the Asian airlines are pressing for greater below-deck capacity. The disagreement potentially calls into question the distinctive oval-shaped fuselage that Boeing is planning for the 797, which sacrifices space for goods in favour of improved aerodynamics and passenger comfort. Based on this, Boeing will have to consider which market will prefer to focus on, especially if it pretends to take advantage of the Asia emerging market with the new aircraft.

Besides, although it is expected that the new Boeing airliner has twin-aisle configuration, the fact is that the capacity target range is found around 200-240 passengers, which is the limit for the twin/single-aisle decision. The problem is that there is no consensus on passenger capacity, now or for the future. The long-range would favour a single-aisle, less overall drag, but if the future passenger load goes up, it would be far easier to stretch a twin-aisle than a single-aisle.

As it was mentioned in previous sections, the initial purchase of a jet represents around 30% of its lifetime costs, being the operating costs the other 70%, such as maintenance, fuel consumption, etc. For that reason, Boeing aims to get profitability from the after-sales service, which is, making money keeping the aircraft in the air. With that purpose, the design of the new 797 aircraft could be focused on capturing a bigger slice of the remaining 70% that comes from operation services over the following decades, which represents a lucrative opportunity for Boeing.

In addition, one of the possible strategies that Boeing is considering for the future is extending its grip on aircraft components that used to be provided by suppliers, such as landing gear, engine coverings, etc. With this strategy, Boeing could reduce some costs of the new aircraft program development, but it would suppose a risk since Boeing would assume part of the manufacturing costs previously borne by suppliers.

13.2.11.2 Factors impacting launch and program timescales

In this section, the main factors that can impact the launch date and the timescales are examined, considering on the first place Boeing's Middle of the Market position respect of its competitors. Secondly, several airline surveys carried out will also identify some of these factors. To conclude, a brief summary of the airlines supporting the B797 will be presented.

Market position

Boeing's position in the Middle of the Market segment, initially staked out by the 757 and 767, not only has not growth but also it has declined in recent years, due to the recent market capture by Airbus with both the A321 and A330 models, offering both narrow and wide-body alternatives for MoM.

With Boeing's market share declining and Airbus share increasing, Boeing has to provide alternatives to face this situation. Currently, the most likely option that Boeing is considering is the 737MAX 10, which consists of a simple stretch of the 737 MAX 9. However, it is likely that this option may not be enough to change Airbus strong position within this market segment. Therefore, Boeing would need a new aircraft in the MoM space to reverse the current situation, since Airbus has succeeded with the strategy of taking the existing 757/767 market and gaining market share.

Key airline requirements

Several surveys among airlines and lessors have been performed in order to assess the industry interest in the new 797. One of them completed by Aviation Week-Bank of America Merrill Lynch detailed airline preferences around the future Middle-of-Market commercial airliner, which strongly supports Boeing's own market assessments. This survey provided the following results [117]:

- 89% of airlines said they would buy a mid-market airplane; 56% would prefer Boeing; 27% Airbus.
- 86% want< 250 seats dual class
- 75% said max range should be < 5,000 nm
- Majority: must burn less than 5 gal/block hr/seat
- 96% need 70-79 m^3 cargo volume or less
- 74% prefer carbon wing and empennage
- 69% prefer carbon fuselage

The survey confirms the industry interest for the new MoM aircraft, with nearly 90% of airlines responding that they would be interested in buying a new MoM jet, and most of those airlines would want it before 2023.

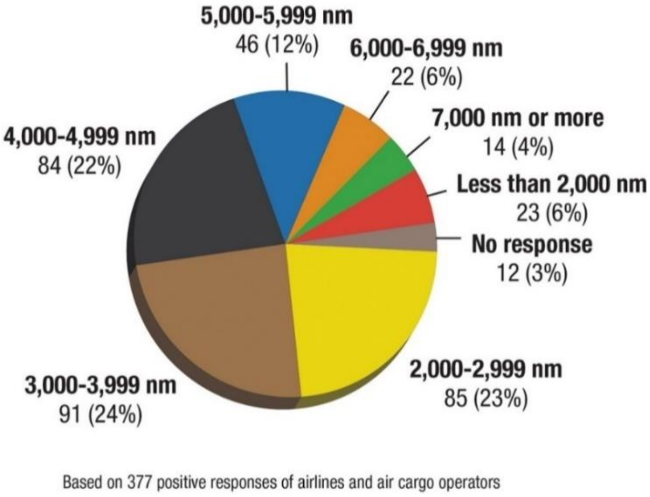


Figure 13.95. Range preferred by operators interested in MoM aircraft. Sources: Merril Lynch Global Research, Aviation Week.

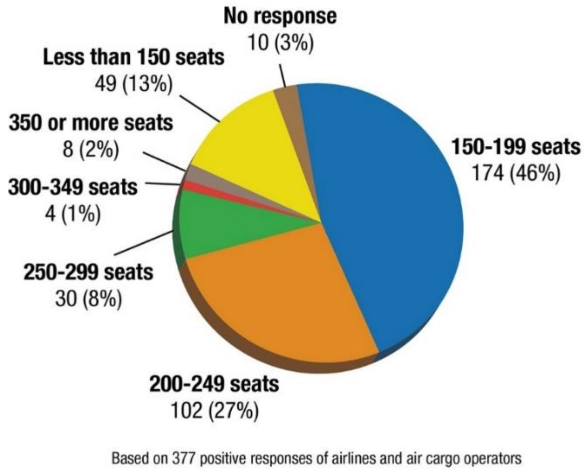


Figure 13.96. Number of seats preferred by operators interested in MoM aircraft, Sources: Merril Lynch Global Research, Aviation Week.

In addition, on the question of size and range, almost half of respondents would prefer an aircraft sized at 150-199 seats, with another 27% favouring 200-249 seats. Respondents were more divided on the range, with 22% favouring 4,000-5000 nm, 24% favouring 3,000-4000nm and 23% favouring 2,000-3,000 nm range [118]. That varied interest suggests Boeing that perhaps a multi-product family could be a possible solution.

Additionally, 69% of respondents would prefer a composite carbon-fibre fuselage to aluminium, and 74% want composite wings and empennage. However, there is also a limit to how much they are willing to spend: 62% of airlines say they would not pay more than $72 million for the jet. Analysts estimate that it translates into a list price of $140–150 million, which seems reasonable.

Among other survey results[119]:

- 83% of respondents say they would remain interested in a MOM aircraft, even if oil prices stayed below $70 per barrel.
- About three-quarters express a need for cargo capacity similar to the Boeing 757.
- More than 80% say having a dual-sourced engine with a “power-by-the-hour” program was very important or somewhat important.
- 15% would use a MOM jet for domestic flights, 30% would for international flights, and 55% would use it for a mix of both.

Airlines supporting B-797

A number of major airlines have expressed interest in the 797, which would fill the role largely held currently by the 767. That aircraft remains in production, but carriers have been keen on acquiring a modern replacement.

Some airlines that have reported to be interested in becoming customers for the 797 are Qantas and Delta Air Lines[120].

On the one hand, the 797 could be a great choice for the Australian airlines' operations by allowing them to fly more passengers on congested domestic routes while opening up new paths to Asia. One example is Qantas, which has expressed its interest for the new Boeing midsize aircraft. The 797 could be a replacement for Qantas' fleet of 28 Airbus A330s, which have an average age of almost 10 years and service domestic and medium-haul international routes. Qantas could also swap out some of its 174-seat domestic 737s for the larger B797. Another possible replacement aircraft for Qantas is Airbus' narrow-body A321neo Long Range, currently in testing, which will seat around 200 passengers and can fly about 4000 nm.

On the other hand, Delta Air Lines is interested in acquiring a new midsize jet for its fleet. The aircraft would be a potential replacement for the ageing Delta fleet of Boeing 757 and Boeing 767 aircraft on long domestic routes and international mid-range flights. The airline will need to replace most of its 757 and 767 fleets during the late 2020s, based on a typical year aircraft- replacement cycle. This could represent a great opportunity for Boeing since it could get a huge number of launch orders from the airline. In the meanwhile, Delta recently ordered several A321Neo to replace the 757s that it uses on domestic routes, which could mean that the airline may opt for Airbus in the upcoming years[121].

13.2.11.3 Production capacity constraints

Scaling up the production is one of Boeing's main priorities within the NMA program. Not being able to produce the products at the same rate as the demand grows could motivate the clients to cancel their orders. On the other hand, exceeding the capacity can lead to an oversized production system, too expensive to maintain and build, and underutilized.

The manufacturers' production capacity is a key factor in the aircraft development process. Depending on the expected demand, it will be required to expand or not production capabilities. However, it supposes a risk because if the manufacturers predict a demand increase in the upcoming years, it is likely that they make an investment to expand capacity. However, if the estimation performed is not reliable and the demand drops, capacity will be larger than demand and the manufacturer will be required to pay for excess capacity that is not used. On the other hand, if future demand is greater than expected by manufacturers, the number of aircraft produced will not be able to satisfy market demand, which would suppose a loss of money.

At present, Airbus and Boeing aim to increase their production capabilities in order to satisfy growing market needs and backlog orders.

On the one hand, Airbus is producing 55 of its A320 family aircraft every month, including the A320ceo older version and the newest A320neo. The company plans are to ramp up production and reaching 63 aircraft per month by beginning 2019 and 75 aircraft a month by mid-2022. This has put significant pressure on its major parts suppliers like Safran, which produces, in partnership with General Electric, most of the engines for the A320neo family. The single-aisle family of Airbus has experienced a gradual increment on the production rates over the last years. In 2018, it changed from 50 aircraft/mo to 55 aircraft/mo. Their suppliers have been manifesting some difficulties to achieve these production rate increments, which has led on many occasions to delays in the delivering dates.

On the other hand, Boeing produces 52 B737s in all its variants every month. Those production rates include both re-engined B737 MAX and B737 Next Generation older versions. Boeing was previously producing 42 aircraft/mo in 2017, currently, it is planning to produce 47 by 2018 and it pretends to reach 57 aircraft a month by 2019. The plans of increasing production rates have caused problems in the supply chain of the company, resulting in late fuselages and engines arriving at the final assembly line, as well as internal problems to complete assembly.

If Boeing takes the decision of launching the 797 by 2025, production capabilities are a big constraint to this issue. New programs imply a big investment in production line efficiency and, to satisfy a big enough production rate, a certain time is needed. Airbus, on the other hand, is playing with the advantage in this segment since its current models; the A321 and the A330 are part of a solid production line that can build 55 and 11 aircraft a month, respectively.

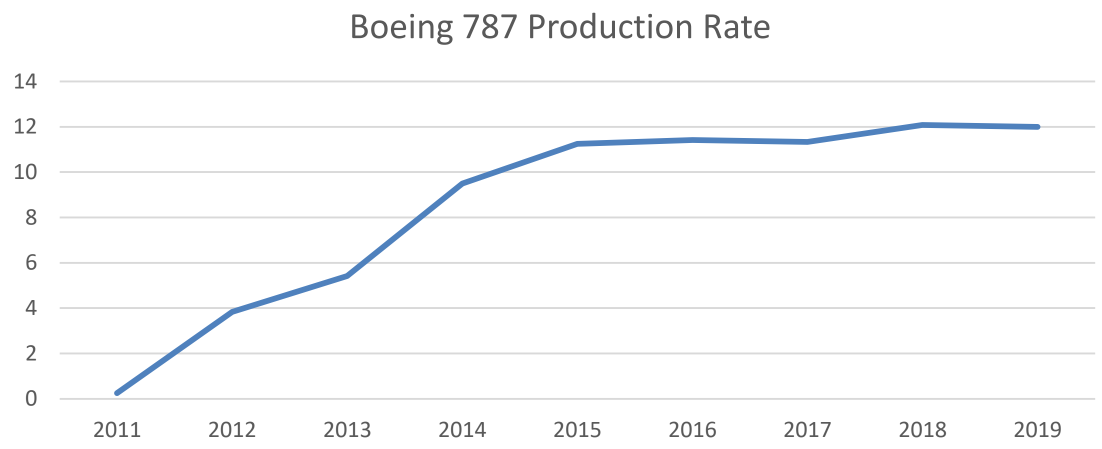


Figure 13.95. Boeing 787 production rate

The production learning curve for a company like Boeing is high. Figure 13.95 shows Boeing 787 production rate over history. Analysing the curves (based on deliveries announced by Boeing), it can be seen that it reaches its steady and peak of production point after only 4 years from the start-of-production date. Similar assumptions can be made into the NMA case, assuming that Boeing's learning curve will remain for this model through the lessons learned from the rest of programs.

Currently, the new Boeing 797 program development is in the concept design stage, that is, in the initial phase. For this reason, there is no data about future orders for the new aircraft and there will be much uncertainty in its calculations. The demand analysis performed in 0 showed that the MoM aircraft demand will be set at around 8700 aircraft by 2040. If the NMA would take, say, 25% to 40% of this market, that would be that they will produce from around 2200 to 3400 aircraft in the considered period.

Depending on the demand captured, production capacity, and consequently the investment required in production facilities, will be different. Figure 13.96 shows the Boeing 797 production rate forecast based on these assumptions and considering the similarities with the 787 program. Two cases have been referenced; first, a demand consisting of 2200 units for the period 2025-2040, which would lead to reach a rate of 15 units per month, 4 units more than what was being produced by Boeing for the 787 by 2019; and second, a demand of 3400 units for the same period, which would force the company to produce 24 aircraft a month in order to satisfy it.

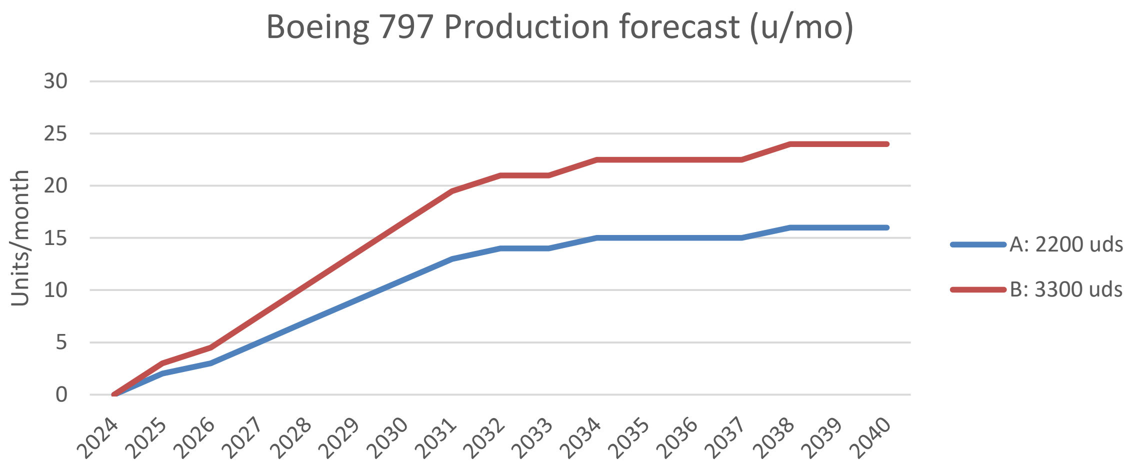


Figure 13.96. Boeing 797 production forecast estimation. Case A: Demand of 2200 units. Case B: Demand of 3400 units.

13.2.12 Manufacturers' strategies

Historically, Boeing has always dominated the medium-size aircraft market. The Boeing 757 and 767 lead this segment offering variants that span from the 200 seats of the B757-200 to the 296 seats of the B767-400, offering ranges that vary from 3,300 nm to 6,590 depending on the version. Since some years, Airbus has reached a strong position within the MoM with models such as the A321neo or the A330, overcoming Boeing in orders and gaining market share. Currently, Boeing's offer in the MoM market segment is the Boeing 737 MAX 8, which belongs to the next generation 737 MAX narrow-body family. However, the A321neo, which is the main rival of the 737 MAX 8, has achieved great success from customers, getting really good sales thanks to its performance advantages, in terms of operating and unit costs.

This chapter discusses the different options that have been appearing over the last years regarding both manufacturers' strategies within the Middle of the Market. Although their own manufacturers have discarded some of the options, this chapter offers insight over the causes that have made manufacturers reject them. Additionally, the manufacturers' preferred options will be discussed, alongside the future product-line of each of the players within the Middle of the Market. The strategies that compose the game analysis performed in successive chapters are extracted from here, and explained in detail thereafter, in section 13.2.13.3.

13.2.12.1 Airbus strategies

The scenarios of a potential Airbus response to Boeing's NMA will be discussed. Options like extending its current product line by stretching the current models, the impact of the long-range variants of the A321neo, or the possibility of developing a new mid-size aircraft are analysed.

Extending the single and twin-aisle segment

In this section, current Airbus' modifications of its current product lines will be analysed. As it has been previously discussed, the Airbus' line up in the MoM is mainly formed by the biggest narrow-body aircraft of the A320 family, the A321, and the smallest wide-body, the A330, with its improved option the A330-800neo. These two options are not specifically designed for the Boeing's Middle of the

Market definition, but airlines operate both aircraft in such routes. If a new Boeing MMA is finally launched, Airbus will have to respond. Its current options in the mid-size market are the single-aisle A321LR, which offers a 190-200 passenger-carrying capacity, and the twin-aisle A330-800neo with 250 passengers. With these two products in its line-up, the company shows a small gap regarding passengers carrying. There are several proposals related to modifications of the current line-up.

Stretching the A320 family

One of the possibilities would be to stretch even more the A320 family and design a longer variant of the A320 based on the A321. The new version would become a true replacement for the Boeing 757, meeting economics of the smaller 797, with a much lower capital risk.

A longer version of the A320 family would need extra-engineering resources, like for example: redesigning wings in order to offer more lift for increased weight, and also a redesigned cabin structure to satisfy meet evacuation rules and infrastructure requirements (airport gates). The engines would be probably the easiest thing to solve since small modifications in the current models CFM LEAP and Pratt and Whitney Gear would probably meet design requirements. Another question to analyse would be how long it can be. A possible approach would be that the new version will be only 2 to 3 meters longer and not add significant extra seating.

Modifying the A330neo

The A330neo is a newer version of the A330 with modern engines and aerodynamics, offering an approximate 14%-17% fuel burn improvement. The A330-900 is competing with the Boeing 787-9 in long-haul routes, whereas the A330-800 is meant to cover the upper Middle of the Market according to Airbus as well as long-haul routes, just like the 787-800. Nevertheless, the range of the A330-800 is 8150 nm, way more than the expected mid-size aircraft. This means that the A330-800 is heavier than the supposed Boeing 797, decreasing economic performance regarding costs per seat.

After discussing the possibility of a longer version of the A320neo, another question that arises is the feasibility of shortening the current A330-800 version of the wide-body aircraft. Would that be possible and technically feasible?

Another option discussed by Airbus would be to introduce a lighter version of the A330neo-800 with shorter range, for crowded mid-haul routes. This variant was previously launched by Airbus for the neo predecessor, the A330-200, for Saudi Arabian airlines. No major adjustments are required to introduce such a variant. The A330neo's engines could be re-rated to a lower level of thrust, and the MTOW reduced to 200 tons from its current capacity of 240 tons. With these modifications, the A330neo characteristics would be very similar to those of the Boeing NMA, regarding range and seat capacity, and could take a chunk of NMA's potential sales.

The influence in the MoM of the A321neo extensions

The Airbus LR is available here and now, and it is being a great replacement of the B757 fleet, capturing a wide portion of the Middle of the Market. The A321LR version of the Airbus A321neo could carve out a respectable chunk of the market before Boeing decides to launch any new mid-size aircraft program.

The Airbus A321LR offers a capacity of 180-200 passengers in a two-class configuration or a single class comfortable configuration, covering routes up to 4000 nm when carrying 206 passengers. In other words, most of the routes between Europe and North America. With this, the A321LR is winning rapidly a fan base among the Middle of the Market users.

When Airbus launched the A321LR, the critical launch commitment did not come from an airline but from one of the biggest leasing companies in the world: Air Leas Corp (ALC) headed by Udvar-Házy. He is one of the most influential customers, along with the Emirates' Tim Clark, in terms of defining requirements and specifications of western-built aircraft. ALC signed a memorandum of understanding for 30 A321LRs, surprising all the market. This assessment caused growth in the airline interest in the aircraft, showing its market potential.

After the big success of the A321LR, Airbus has been studying the possibility of stretching, even more, the range of the model, designing an upgraded aircraft to cover the routes that the A321LR version cannot operate, as well as for those who are looking for a more efficient replacement of the B757. The goal is to have an increased MTOW of 100ton instead of the current 97ton. In order to accomplish this figure, the aircraft will have to possess some minor modifications incorporated into its design and assembly, including a strengthened landing gear and reinforced fuselage structures.

To accomplish these modifications, the Airbus A321XLR will have to account several weight-saving modifications, as well as increasing fuel capacity while maintaining the same wing. Regarding engines, the CFM LEAP and PW1000G options would be the only one available just like the rest of the A320neo family.

The 17th June of 2019, Airbus finally announced the development of the A321XLR with 4700 nm of extended range, 15% bigger than the A321LR's (4000 nm). The announcement was made at the Paris Air Show, closing up to 200 orders to this model.

Is there a place for a new Airbus MMA?

Airbus argues that the extended range of new generations of existing aircraft gives airlines all the capacity they need for a range of operational missions. The new segmentation proposed by the manufacturer: small, medium, large and extra-large categories of aircraft, reflects better the way airlines operate aircraft, according to it. Airbus solidly trusts in the versatility of the A321neo as the longest version of its single-aisle family. The company justifies itself saying that the demand is not wide enough for needing a clean-sheet design.

Whatever is Boeing's final strategy, Airbus will have to respond with either a modification of its current products line, which implies fewer costs and risk or a completely new Airbus MoM aircraft, which is less probable according to Airbus 2018 and 2017 financial records. The two last all-new programs launched by Airbus were costly for the company. The A380 did not reach the demand they expected in the market, and the A350 initial design had to be modified to reach airlines' requirements in response to the Boeing 787. In addition to this, the recently developed military aircraft A400M has had several problems in the previous years, related to performance and requirements meeting. This has cost the company several million as well, including delays and retrofits.

All these topics make more and more difficult the decision of developing a new aircraft. Modifying and upgrading existing products would be economically more effective for the company. Despite these comments, the reality is that there is still no mid-range wide-body aircraft in the market. Survey's results displayed in Section 13.2.11 show that some airlines are demanding a wide-body to operate in short-haul saturated routes during the peak time of the day, and able to fly over the Atlantic during the off-peak time. In the early 90s, Airbus tried to develop such aircraft but it was not able to maintain the number of flight cycles per day. If Boeing finally decides to launch the aircraft, it will surely absorb a big part of the market, and it might force Airbus to move on with a new design, but the question is if the market is wide enough to stand two similar models.

Although this case is the less probable, it is analysed subsequently on a dynamic game analysis, where one of the strategies of Airbus is to develop a new Airbus MMA to compete against the 797, after being forced to do so. A hypothetic model of this aircraft, similar to the Boeing 797's expected capabilities will be used for developing the gaming analysis.

New engines to revive the A380

The A380 is surviving in marginal production numbers with only 10 aircraft manufactured per year. The last order of 20 aircraft from Emirates supposed the salvation of the program. In 2017, Airbus announced a "plus" version of the superjumbo, with improved aerodynamics (new winglets) and cabin re-structure that allowed 12 more passengers. This small modification allows a reduction of up to 14% in cost per passenger and 4% fuel reduction.

Although Airbus has not announced any plans of the re-engined version of the current A380, the called "A380neo" with a new generation of engines like the ones used in the A350 or the neo versions of the A330 or A320 could increment the sales of the aircraft. The current options available are the GP7000 manufactured by Engine Alliance (a joint venture between General Electric and Pratt & Whitney) and the Rolls Royce Trent 900. Both options have an 8.7:1 high bypass ratio.

Newer generations of engines developed by CFM and P&W use ultra-high bypass ratios of about 12.2:1, offering a notable fuel reduction. If this type of engines were used in the A380, the operating cost would be reduced significantly.

After the Airbus announcement of February 2019 of ceasing the production of the A380, this study case was withdrawn of the core of the study. Nevertheless, the reader is referred to Annexes to find out more about this topic.

13.2.12.2 Boeing strategies

With Boeing's market share in the MoM segment declining and Airbus share increasing, Boeing has to take some action to change this situation. The main option that Boeing is considering is the new MMA aircraft, but there are other alternatives to be considered to face the current Airbus market position as well as the threat of the A321neo. Some of these alternatives are discussed here.

Evolution of the B737 and the B787

Boeing's best-sellers 737 and 787 hold a respectable share of the lower- and upper- layers of the Middle of the Market, respectively. The Boeing 737 MAX 8 and 9 operate many of the routes between 2500 to 3000 nm, and the 787 holds more than the 30% of the MoM routes nowadays. These products compete with the A321 LR and XLR variants, but each of them is designed for a different mission, which makes them less flexible than the Airbus competitor. Boeing has been proposing different options to modify these aircraft, but none seems to be feasible.

Boeing 737 MAX 10

Boeing is developing a simple stretch of the 737 MAX 9, dubbed the 737 MAX 10, which would be a solution less complicated, from a technical and financial perspective, with a development cost of 1,5 to $3 billion, according to analysts' estimations. Design changes for the 737 MAX-10 include a fuselage stretch of 66 inches compared to the 737 MAX 9 and levered main landing gear. Other changes include a variable exit limit rating mid-exit door, a lighter flat aft pressure bulkhead and a modified wing for low-speed drag reduction. The extension will boost capacity, allowing adding 12-18 passengers more than the 737 MAX 9. As a result, it will be competitive on unit economics with the A321neo.

According to Boeing, the MAX 10's advantage will be lower costs and less weight. Additionally, it is expected a 5% lower fuel burn for the MAX 10 versus the A321neo and operating performance at 97% of that of the A321neo. Nevertheless, the aircraft has a shorter range of 3300 nm, versus the 4700 nm of the Airbus A321 XLR.

The entry into service of this aircraft is expected by July 2020. By June 2019, the aircraft counted with more than 500 orders from several customers, much less than the B737 MAX 8 and its competitor A321neo.

Boeing 787 Dreamliner

The Boeing 787, dubbed the Dreamliner, is a medium-sized, twin-aisle, wide-body airliner. The aircraft can carry between 217 and 323 passengers, depending on the type (787-8,-9 or-10). The 787 is able to provide the flight range of large aircraft to medium-size reactors and provides airlines with unprecedented efficiency in terms of fuel consumption. It consumes 20% less fuel than any other airplane of its size in similar operations. Additionally, it is important to highlight the significant reduction of its total weight, due to the use of composite materials in most of its construction. Although the 787-9 and 787-10 surpass the target range and passenger capacity planned for the new mid-size aircraft, Boeing is considering using the 787-8 variant as an option for the MoM segment. The 787-8 is the base model of the 787 family, which can accommodate 210 passengers in a three-class configuration, with a range of 7650 to 8200nm. Boeing aims to replace part of the 767 fleet (the 767-200 and 767-300) with this aircraft as well as to allow airlines to expand to new markets, where large aircraft would not be economically viable. It is even possible that Boeing considers a new shorter variant of the 787 to compete in the MoM market in the following years.

Critical timeframe decision of the NMA

Boeing's new midsize aircraft is considered mainly to be a substitute of the Boeing 757 and Boeing 767 older models in the Middle of the Market segment. These two models have stopped production in 2013 for the 767 for its passenger version and in 2004 for the 757. This indicator shows that most of the aircraft are prior to its date of retirement. By November 2018, the mean age of Delta airlines Boeing 757 fleet was 21,2 years and American airlines' fleet was 19 years by average. The lately trends on aircraft retirement show that means retiring age is around 25 years for single-aisle aircraft. This means that most of the B757 are about to reach the limit retirement age.

Boeing has announced plans of proposing launching decision by 2020 and entry into service by 2025. Most critical factors of this decision are the diffuse demand seen by engine manufacturers like General Electric, which does not believe that the market is wide enough to justify a new design. If Boeing decides to go ahead with its decision and manufacture the new aircraft, there are several timelines to take into account. The first flight should not be later than mid 2023-2024 for entering into service in 2025. Boeing's latest new design, the 787, suffered 3 years delay due to problems in the engines that delayed the first flight. Moreover, the 787 suffered several post-launch problems due to battery fire problems.

Although Boeing claims that the 797 would be a more conservative design, using technologies developed in the 787, it is still a completely new aircraft, and there is always some uncertainty about dates. In the Middle of the Market, time is a very critical factor due to the imminent replacement of the current fleet, especially taking into account that Boeing's competitor options are already on service.

Apart from the 797, Boeing does not offer much more alternatives. The Boeing 737MAX 8 and 10 versions competing in the lower bound of the Middle of the Market have lately been overcome by Airbus A321neo orders. If this short demand of mid-size aircraft keeps being delayed, the A321neo orders may capture a wide part of the market and maybe in the launch date, it would be too late to capture the attention of airlines. There is a small gap that needs to be covered and the timeframe is a really important factor.

Abandon the 797

Airbus has gone a step ahead in the Middle of the Market with the A321neo, taking 8:1 orders compared to Boeing. The American manufacturer has to close carefully the business case of the new mid-size aircraft. Even without the advantage in the market, Boeing believes that its new aircraft will be able to open new routes between cities as the 787 did in the past, and it thinks there is demand where others believe there is not. Nevertheless, there are several reasons that might force Boeing to abandon the 797 project, those are:

- Market analysis in 0 showed that the potential MoM demand is worth around 8700 aircraft from 2018 to 2040. Airbus options are already flying or planned to be in service by 2023, taking a big part of this market. At the same time, wide-body aircraft are taking part in this market as they were operating in it for the past years. If the decision is delayed too much time, Boeing might be forced to abandon the program, due to the lack of demand for a clean sheet design.

A too elevated development and manufacturing cost that will directly impact on selling price. The new mid-size aircraft should not be sold by more than $100 million to compete with the incumbent options of the market. Although public prices of aircraft are announced, real data shows that manufacturers apply discounts of even 50% from the public price to the airlines[84].

13.2.13 Definition of game model features

13.2.13.1 Game theory applications in the aerospace sector.

Game theory involves a set of concepts and tools to analyse decision making under specified rules in competition, conflict, cooperation or interdependence situations. This type of studies focuses on the analysis of strategic interactions and optimal decision making, considering that all participants make rational decisions and each one tries to anticipate the possible actions and reactions of their rivals.

A strategic game reflects a situation where two or more participants are faced with choices of action. The choices of action may imply gains or losses for each participant, depending on what the others choose to do or not to do. Therefore, the final outcome of the game is not determined by the strategies or actions of a single participant, but instead, it is the result of the combination and interaction of the strategies applied by all the participants.

It is also necessary to consider that participants under uncertainty take decisions because they do not know for sure what the other players are going to decide. In the end, game theory studies how participants, in this case, aircraft manufacturers, make their decisions when they need to take into account the strategies and actions of the others.

This part of the study performs a game theory analysis of the impact of manufacturers' competition on the evolution of the Middle of the Market segment, and in particular on the introduction of a new aircraft model specifically designed for this sector by one of the manufactures. Game theory analysis is used to model competitive forces influencing manufacturers' decisions, what will allow us to test manufacturers' strategies and decisions, and to determine their outcomes in a competitive market, based on the assumptions performed throughout the study.

Game theory analyses the long-term result of the different strategies that each one of the manufacturers may adopt to exploit the Middle of the Market segment. It also helps to understand how different possible future scenarios could influence the result of these decisions and strategies. It will clear up to what extent the outcomes of the decision to re-engineer current aircraft models or to design a clean-sheet aircraft program, may be altered by external factors such as an increase in fuel cost, technology-forcing regulations, subsidies, variation in the expected demand, the extension of low-cost carries for these segments, etc…

A game theory analysis enables the discovery of the equilibrium of multiple, competing players' who act in their own best interests. Understanding how competition affects the decision to invest in new aircraft designs can assist policymakers in developing plans of action to improve the sector.

Game theory frameworks have already been used in the past to analyse competition between aircraft manufacturers. A classical and well-known example of a game, often used in negotiation, is the prisoner's dilemma. In this example, two players must choose, without communicating with each other, either to cooperate or betray. Under the name of the Developer's Dilemma, Boeing vs. Airbus, it has also served to explain the competition between Boeing and Airbus in the '90s in the development of a new superjumbo [122].

The effect of external forces in competitive scenarios in aviation has also been studied by game theory in the past, in particular, the impact of governmental subsidies on the game conditions and outcomes has been researched by [123].

Brander and Spencer [123] showed how government subsidies could be used to change the initial conditions of games between non-cooperative international rivals. Krugman [124] used hypothetical payoff matrices to show how government subsidies could enable domestic firms to increase profits in excess of the subsidy amounts by deterring foreign entry and allowing domestic firms to capture excess returns, increasing social welfare.

In Briceño's PhD [125], a game-based methodology is used to select the most appropriate R&D projects for an aircraft manufacturer under uncertain competitive scenarios, analysing competitor positioning and forecasting the impact of technical design choices on a project's market performance.

Lately, Siang [126] applied 3-player cooperative and non-cooperative game-theoretic models in the transportation and logistics industry to analyse China's aviation sector and the port industries of Malaysia and Singapore.

13.2.13.2 Game model elements

The game-theoretic framework allows accounting for the presence of multiple competitors, all of whom make rational decisions in accordance with their own best interests. It is assumed that all players will act rationally and all of them know that other players make rational decisions. That is, the goal of each individual is to maximize their well-being. Therefore, they will make an optimal choice according to the beliefs they have about the other players' decision making. Each player will decide to choose one strategy or another according to the knowledge each one has about the current situation.

These assumptions enable the discovery of the Nash equilibrium of competing players' strategies. The Nash equilibrium is the predicted strategy for each player that is the best response to the predicted strategy of all other players. In a Nash equilibrium, firms are assumed to be capable of predicting correctly the behaviour of their competitors. Starting from the premise that players are rational, they will carry out rational decisions and each of them will have a unique rationale strategy. Nash's equilibrium identifies stable strategy profiles, so no player has any incentive to deviate from the established if the other players make the decisions expected of them. Therefore, the set of rational strategies of each player will form the Nash equilibrium.

Here, it is important to point out that there are two kinds of strategies, pure strategies and mixed strategies. In a pure strategy, the payoff of a choice is always better than the payoff of the other choice. A pure strategy provides a complete definition of how a player will play a game. In particular, it determines the move a player will make for any situation they could face. But sometimes, one choice is not always better than the other. Then, the player tends to mix between each choice depending on the timing and circumstances, and it is called a mixed strategy. A mixed strategy is an assignment of a probability to each pure strategy.

A game theory analysis is based on the two key elements mentioned below:

1. the structure of the game, and
2. the strategy's payoffs to each player.

Defining the structure of the game means to make a series of assumptions about how participants will define their course of actions and how those actions will turn up into results. For example, it is necessary to define how many players will act in the game and how they will interact with each other. The game could reflect situations of competition, conflict, cooperation or interdependence. In non-cooperative games, players compete with each other, without considering negotiation scenarios or the development of a binding contract between them, that is, players, make their decision independently.

It is also necessary to specify whether the game is sequential, i.e. one player moves first and then the rival follows, who knows the decision already taken by the other player. The other case to consider is when both players take decisions at the same time without knowing what the other is going to decide.

Furthermore, games can be static or dynamic. In static games, also known as one-short games, players interact with each other only once. Players make decisions simultaneously and these decisions are made without knowing the decisions of each other. A good example of this type of game would be a secret ballot. In dynamic games, also known as repeated games, players interact with each other over an extended period of time. In these games, players, when making decisions, obtain prior information from other player's strategies or from the results of random moves that have been made.

The definition of the game structure involves also the clear identification of the decisions or course of actions each player can take, that is, which is known as strategies. The strategies and decisions taken by each company will influence the company outcomes and performance, and it is necessary to have enough knowledge on how this decision will be transformed in results, including economic benefits or losses. As explained in previous paragraphs, strategies can be pure or mixed.

The second element of the games is indeed the calculation of the payoffs derived from the company strategies. To calculate the payoffs it is necessary to develop a valuation model that allows estimating gains or losses derived from the company actions.

Therefore, when performing game analysis, the research approach is three-staged.

- First, the establishment of static and dynamic game structures for the Middle of the Market two players problem.
- Second, the aircraft program valuation model defined in previous chapters is used to estimate manufacturers' payoffs under different market share, fuel price, and demand scenarios.
- Third, a game theory analysis is used to model competitive forces impacting manufacturers decisions.

The purpose of this analysis is not to determine the aircraft manufacturer profitability, but to estimate the rank ordering of payoffs to determine how changes in the market structure may change the equilibrium game outcome, using a consistent framework for comparison. In the absence of aircraft program economic data, all the information used in the study is public information. The analysis is sustained on reasonable assumptions based on publicly available data sources.

13.2.13.3 Structure of the Middle of the Market Aircraft Competitive Game

The Middle of the Market competitive game is structured into two different types of competitive games:

- Static games: in static games, both manufacturers interact only one time by taking a decision at the beginning of the analysis period. The consequences of this decision are observed over time.
- Dynamic games: in dynamic games players interact several times along the period of analysis and have the opportunity to update their decision at fix times, based on the evolution of the market, on the result of previous decisions as well on external factors.

The structure of both of them is explained hereafter.

Static Games

The static games represent the decision space of both manufacturers as nowadays. When phasing the evolution of any aviation market segment, each manufacturer would have four generic strategies at its disposal:

1. maintaining their existing product lines, with incremental improvements over time;
2. re-engineering their existing airframes (either with an extension of the structure of the aircraft or with upgraded engines), providing superior performance improvement;
3. developing a new clean-sheet design aircraft that offers the greatest improvements;
4. exiting the market;

However, these four possible general strategies need to be adapted to reflect the exact conditions and alternatives of Boeing and Airbus in the Middle of the Market today: i.e. the existing products lines; their possible incremental improvements and the margin for re-engineering; their current market penetration; and their backlog and demand expectations. All these conditions may limit or modify the available strategies.

Today, both participants, Boeing and Airbus, have aircraft in production that serves the Middle of the Market. In **Error! Reference source not found.**, a detailed analysis has been performed in which are nalysed the aircraft of both manufacturers that currently operate in the MoM. Characteristics, advantages and disadvantages of each model have been discussed, and detailed information about those models is provided in Annex 1.

At 0, we have analysed the distribution of those models for different routes lengths in the MoM. In order to define strategies, is it important to acknowledge the current level of penetration of each model, as well as the possibilities of extension and evolution of each model for maximum exploitation of the MoM, which has also been discussed in 0.

As indicated in 0, Boeing is currently dominating the MoM operation with a market share of 56%, operating a set of aircraft that includes 757,767, 737 family, 787, 777 (and 747 with a very small percentage, the 3%). The remaining share is exploited by Airbus models, with the following fleet: 320 family, 330, (and with a very little presence 380, 340 and 350, between 1 and 3%).

However, none of these models is optimised for this market. The reengineering possibilities of each one of them, in order to adapt its performance to the route length and demands of the MoM, has been studied at 0. It has been explored up to that point both manufacturers can extend their current product lines by stretching or shortening current models, by re-engineering them of by upgrading their engines.

As a result of this analysis, we have concluded that Airbus is in a better position nowadays to extend its current products, whereas Boeing is in a more limited situation. This fact explains the position that both manufacturers are publicly defending regarding the Middle of the Market.

Airbus claims that the MoM can effectively be exploited with its current products line and its possible extensions; and that the size of the market does not justify the development of a new clean-sheet aircraft. This is sustained on the fact that Airbus took the decision several years ago to stretch the A321 and adapt it to longer routes; and consequently, the company enrolled in the production of the A321RL. This aircraft is expected in the market in short and Airbus has almost made already the investments required to re-engineer the A320 family. Additionally, this model still has some extension capability. Airbus has announced that it will pursue that option in case market opportunities or competition will require it, although the decision is not yet formal. Airbus has discarded in the sort time the possibility of a new aircraft for this segment. That means that Airbus today has only two possible viable options out of the four general ones previously mentioned:

- Airbus static-a: Maintain the current product line, i.e. A321RL.
- Airbus static-b: Re-engineer A321RL and develop the A321XLR.

It has to be noticed that because A321RL is a new model, the manufacturer will stick to this technology at least for a period of 10 years, to make it profitable. So, even if a decision for re-engineering was taken, the new A321XLR program could not start before 2025, and its estimated data for EIS will not be available before 2030. This will influence the calculation of the company payoffs.

On the other side, the 737 MAX family is today bestselling products (except for the punctual situation derived from last B737 MAX 8 accidents). Boeing is harvesting today the outcomes of the anticipated decision of extending the 737 product line, few years in advance regarding A321LR. However, the possibility to further extend 737 MAX has come to an end. That means that Boeing today has only two possible viable options out of the four general ones:

- Boeing static-a: Maintain the current product line 737 MAX,
- Boeing static-b: Develop a new cleans sheet MMA - 797.

Moreover, as stated in 0, Boeing is in a critical situation, because despite dominating the market today, if nothing changes, the EIS of the new A321LR will imply the inversion of dominance by the year 2040. Airbus would become the leader in the sector with more than 60% of the market and Boeing would lose its dominance, reducing its market share down to 40%.

So, in this situation, Boeing is more than never pressed with the need to confirm a course of action. Airbus is currently in a more advantageous situation, as the good prospects for A321LR will grant Airbus a dominance position; and therefore, Airbus is not hurried to take a decision yet about the A321XLR. Airbus could delay the decision, and wait to see how Boeing reacts, without losing market opportunities.

In the static game, we reproduce the hypothetical manufacturer's space of decisions in 2020. Figure 13.97 summarises the possible strategies in this context and the structure of the game. It can be observed how the generic four original strategies have notably simplified when particularised for the circumstances of this game.

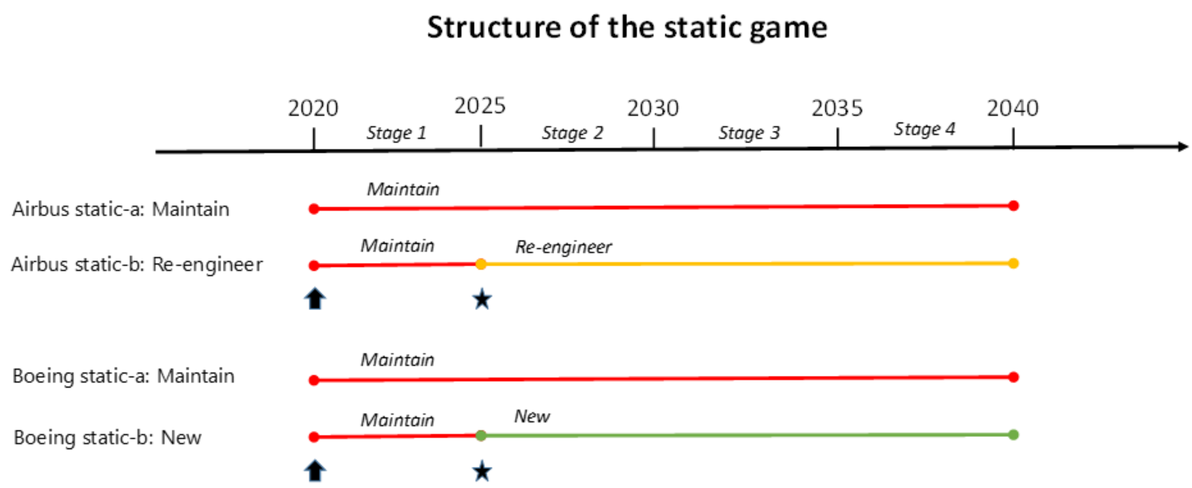


Figure 13.97.Strategies and structure in the static game.

We considered that decisions will be done simultaneously by both manufactures in 2020, and their consequences will be analysed through a period of 20 years, which corresponds to the manufacturer's demand forecasts and oil price forecasts. The static game allows us to foresee the impact on the long run of the decisions that both companies have to take now. Static games enable an understanding of current factors influencing the manufacturer's decisions, although, in reality, players are engaged in a long-term game that extends beyond the 20-year horizon.

For the static games, manufacturers make their decision to proceed at the beginning of the time period examined. It is assumed that there is a 5-year delay from when a decision is made to when the aircraft enters into service. Therefore, a decision to develop a new aircraft includes the production and sale of the existing aircraft for 5-years until the new aircraft enters service. Although the development time for a re-engineered aircraft may be less than that for a new aircraft, it is assumed to be the same to simplify the structure of the game into four five-year stages.

The static games are also intended to demonstrate how various external factors are likely to affect the outcome of the competitive game. To that aim, we have identified a set of external conditions that might affect the outcome of the competitive game and used them to generate alternatives scenarios under which the static game will be played. In our study, we considered a reference scenario and also alternatives scenarios that correspond to variation in possible external factors, more or less volatile. The different scenarios correspond to:

1. Reference scenario.
2. The expectation of Low Fuel Prices.
3. Technology Forcing Regulations.
4. Manufacturer Subsidies.
5. The expectation of High Fuel Prices.
6. Increase in Airport Congestion.
7. Development of low-cost carriers in the MoM sector.

All these scenarios are described in detail in further sections.

Dynamic game

As stated before, in dynamic games players interact several times during the period of analysis at fixes epochs. At each decision point, they will have the opportunity to update their decision based upon the evolution of the market and the result of previous decisions. This analysis allows understanding the evolution of possible decision along the time, and how previous decisions impact posteriors ones.

The strategies of both manufacturers in the dynamic game are defined slighted different from those in the static game. Figure 13.98 outlines the decision space in this game.

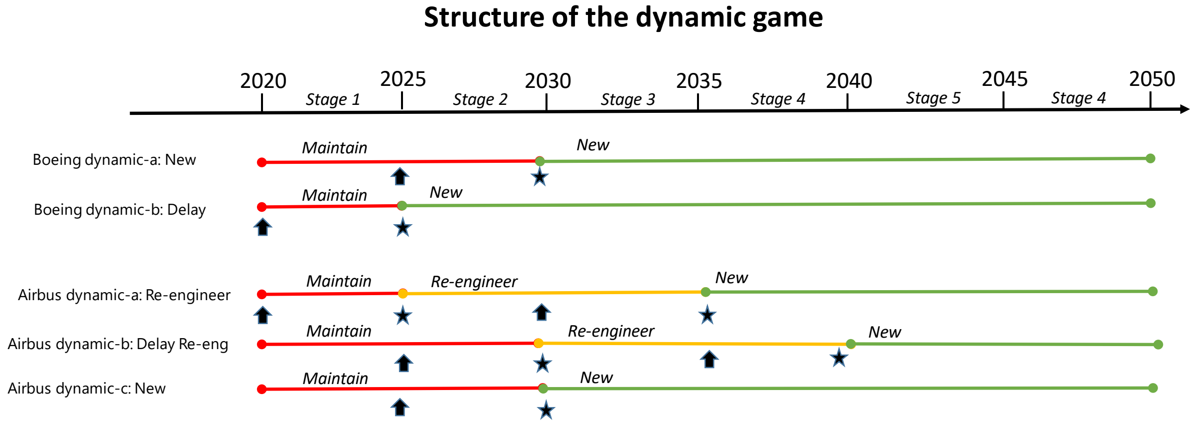


Figure 13.98. Strategies and structure in the dynamic game.

A 30-year period of the analysis is used for the dynamic game to give more time to observe the consequences of the decisions. As can be seen, the 30-year timeline is divided into intervals or stages of 5 years. Manufacturers will update their decisions at 5-year increments. The first opportunity for a decision is in 2020. Decisions are indicated in the timeline with arrows, and the corresponding entry into service date are indicated with asterisks.

Is assumed a 5-year delay between a decision for new or reengineer aircraft and its entry into service. Therefore, a decision to develop a new aircraft includes the production and sale of the existing aircraft for 5-years until the new aircraft enters service.

It is assumed that a manufacturer would produce a re-engineered aircraft for 10-years to receive a sufficient payback on its investment. Therefore, in the dynamic game, the re-engineering strategy includes the decision to proceed with a re-engineered aircraft and with a new aircraft, 10 years later.

In each case, it is assumed that players' moves in the game terminate when they decide to develop a new aircraft.

In this context, as can be seen in Figure 13.98, Boeing still would have two basic strategies: either maintain the current product line or to develop a new clean sheet MMA. However, in the dynamic game, we may study the consequences of taken both decisions at different time periods.

In a first instant, Boeing could decide to delay the decision of launching the new MMA because of several reasons, e.g. uncertainties about the technical feasibility of the MMA expected difficulties in the development of the new engines for the MMA, recent drawbacks with model 737 MAX 8, wait to see how the A321LR program evolves, etc... In this case, Boeing will maintain its current models for a period of 5 years. After this interval, Boeing will ultimately need to take the decision of starting the development of the MMA if it does not want to risk losing market in favour of the new A·321RL. This option is named as Boeing dynamic-a) in Figure 13.98.

Alternatively, Boeing could decide to launch the B797 program in 2020 as announced. This option is named as Boeing dynamic-b) in Figure 13.101. In both cases, a 5-year delay from when a decision is made to when the aircraft enters service is assumed.

The alternatives of Airbus in the dynamic game will vary depending on when the company will take the decision of re-engineering the A321RL or not. They will also vary depending on whether Airbus will be forced finally to go for a clean sheet design to maintain its position in the market or it could defend its position by evolving the A321RL. As A321RL is not yet in service, and a 10 years period of technology blocking is considered, Airbus cannot decide to re-engine that model at least before 2025. Possible alternatives for Airbus in the dynamic game are as follows:

Airbus could decide to re-engine the A312LR in the first stage (2020-2025) with an EIS in the second stage (2025-2030). Ultimately, after producing the re-engined aircraft for a period of not less than 10 years, the firm will have to decide whether or not to go for a new aircraft. This option is illustrated as Airbus dynamic-a) in Figure 13.98.

Airbus could also decide to delay such a decision for another 5 years, in the second stage (2025-2030). This option is illustrated as Airbus dynamic-b) in Figure 13.98.

Airbus could also decide, depending on the evolution of the market, to go for a new clean sheet without intermediate re-engined versions at stage 3. This option is illustrated as Airbus dynamic-c) in Figure 13.98.

In a market in equilibrium, none of the manufacturers will have any incentive to innovate in new programs or technologies. This is not the case of the MoM. Today, the market is unbalanced towards one of the manufacturers, but the other one has already taken actions that will conduct to the inversion of the situation if nothing else is done. So, there is a real force for technological innovation in this market.

Although initially, the Airbus position is to not develop a new MMA and to opt for reengining the A321RL, the dynamic game gives the opportunity to evaluate whether this second alternative will be good enough to keep its predominance in the market; or if at a certain moment in time, Airbus will be obliged to reconsider this initial strategy.

Delaying the decision provides manufactures more flexibility for future actions but gives competitors an opportunity to develop a superior aircraft earlier. On the contrary, when the manufacturers commit to a course of action, re-engineer or new aircraft, they lock into a technological level for 10 or more years (to recover part of the investment) and assume the risk that comes with big investments.

To understand properly the impact of delaying a decision in the game, it is necessary to considerer how technology evolves along time in an active market. Let’s take for example the expected evolution of fuel efficiency.

Figure 13.99 reflects the relevance of performance improvements achieved in fuel efficiency by introducing a new clean-sheet aircraft vs the performance improvements achieved by re-engineering current existing product lines.

Based on historical data, incremental improvements to an aircraft generally amount to ~1%/annual fuel intensity reductions. Incremental improvements in re-engineered aircraft (particularly with new engines) might rise up to 2%; while incremental improvements can go up to 3% in the new clean-sheet design (because of its brand-new technology).

Re-engineered A321RL is expected to offer up to 15% fuel savings operating in the Middle of the Market. The new Boeing B797 clean sheet design would offer a fuel efficiency improvement on the order of 25%. The more the decision for the new design is delayed, the greater this improvement might be due to the consolidation of new technologies, today at low TRLs, with expected improvements in fuel efficiency on the order of 70% by 2040. Therefore, in the long term, there is a performance advantage to delay the design of a new aircraft.

In Figure 13.102, we can observe how Airbus will benefit from the re-engineering of the A321RL in 2020: a fuel efficiency gained around 15% will give Airbus a competitive advantage. If Boeing confirms its decision for the B797 in 2020, it will be locked with the technology available in 2020, providing fuel efficiency improvements of 25% and performance advantage when it enters service around 2025. To recover again a competitive advantage, Airbus could opt between extending and improving the A321RL or go for a new MMA as Boeing has done.

Due to payback periods on the order of 10-15 years for large commercial aircraft programs, when a manufacturer commits to a new or re-engineered aircraft, they lock into the technology level for the duration of the program, enabling only incremental improvements.

Locking into a technology may leave a competitor vulnerable to its aircraft being obsolete five or ten years later, around the same time manufacturers hope for their programs to become profitable and benefit from reduced production unit costs through learning effects. Aircraft that have superior performance gain market share and yield higher sale prices. Although manufacturers can always purchase market share by dropping the sale price, this strategy reduces profit margins.

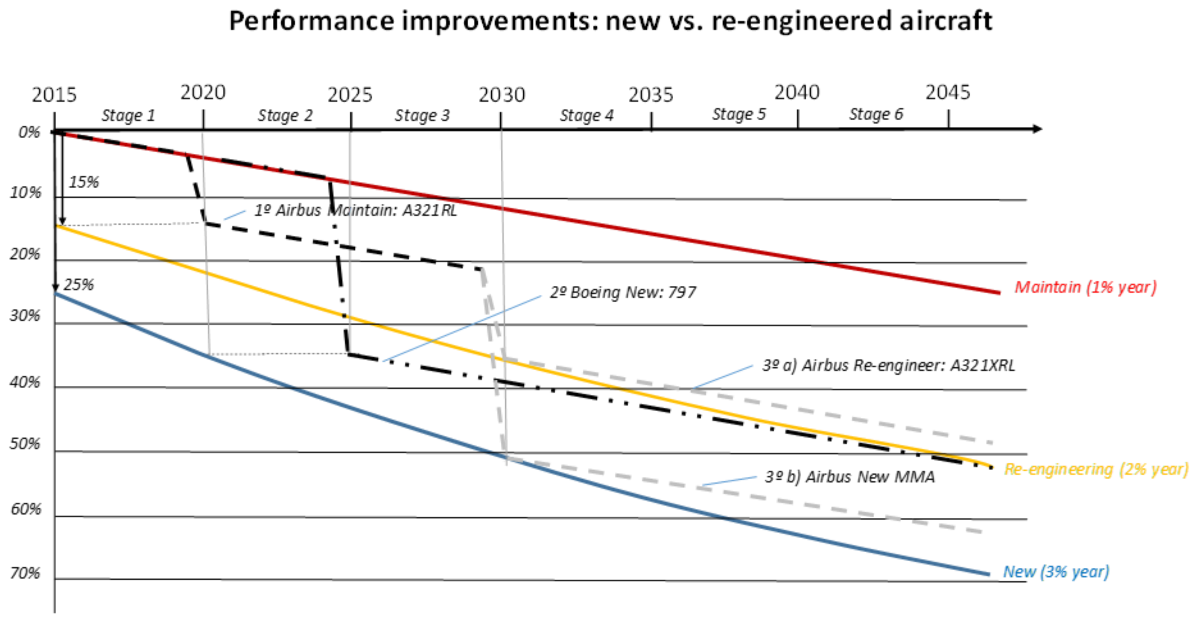


Figure 13.99.Potential Fuel Burn Improvements of Future Technologies.

13.2.13.4 Definition of Scenarios

When designing an aircraft, the manufacturer must balance a variety of criteria, some of which are volatile, such as fuel burn and price of fuel, demand, supply chains and manufacturer facilities, technologies, regulation, etc. Aircraft are generally optimized for one speed, altitude, stage length, payload, and fuel price, and therefore, consequently, design compromises are inevitable. Decisions based on optimistic forecasts may result in severe financial consequences, whereas overly pessimistic forecasts can limit the potential upside of an aircraft program. These sources of uncertainty are included in the games investigated.

In our study, we considered a reference scenario and also alternatives scenarios that correspond to variation in possible external factors, more or less volatile. Those scenarios are:

1. Reference scenario
2. The expectation of Low Fuel Prices
3. Technology Forcing Regulations
4. Manufacturer Subsidies
5. The expectation of High Fuel Prices
6. Increase in Airport Congestion.
7. Development of low-cost carriers in the MoM sector.

Reference scenario

In the reference scenario, fuel efficiency and aircraft operating costs are the key drivers for airlines buying decisions. The forces governing market share, described in 0, favour the aircraft models that implement latest fuel efficiency technology, improved engines, lower weight and in general reduced operating costs.

In this scenario, manufacturers share incentives to innovate and to propose re-engineered versions of current fleets or new clean sheet designs.

Additionally, gains in efficiency will justify that manufacturers might increase the selling price of new models, as discussed in Chapter 13.2.6, as far as they are offering features and significant performance improvement to justify price increase through the aircraft lifespan.

The reference case will be explained in detail in section 13.2.13.5 "Application to the reference scenario" where it has been used as an example for the model's calculation in the valuation program.

The expectation of low Fuel Prices.

The main incentive to develop a new aircraft is to gain market share, and therefore obtain greater benefits than their competitors. However, under a scenario of expectation of low fuel prices, fuel efficiency is not expected to be the main driver of the market share, and the forces governing the market share today will remain more or less stable. Other factors will dominate the buying decision by companies, such as maintenance costs, other operational costs, manufacturer fidelity, the economy of scale, number of seats, etc.…

In this scenario, neither Boeing nor Airbus will have an incentive to invest in fuel efficiency technologies, either in the airframe or in the engine. None of them can increase the selling price of a new aircraft due to the fact that the savings in fuel cost are not significant considering the lifespan of the aircraft.

In this case, the best strategy to gain more market share would be to reduce production cost and decrease the selling price of the aircraft. This option will be very complicated for a new or re-engineered aircraft because it will be needed a great investment and a high demand to be able to reduce the unit cost of a new and more efficient aircraft working on the learning curve.

Technologies Forcing Regulations.

Data show that regulation has become more effective than fuel prices evolution to improve fuel efficiency and reduce emissions, and it has been the single measure driven noise reduction.

If low fuel prices are expected, the manufacturers would not have an incentive to develop a new aircraft or to make re-engineering. In this condition, regulation can be the only driver promoting innovation. Therefore, governments can implement a technology forcing regulation to obsolete existing aircraft product lines, forcing manufacturers to re-engineer or develop a new and more efficient aircraft, incorporating improvements in fuel burn and in the reduction of harmful emissions, or in other environmental impacts such as noise.

Technology forcing regulation has a bigger impact on older and outdated aircraft product lines, even forcing manufacturers to stop production and develop new aircraft. This type of measures has the additional effect of raising market entrance barriers by requiring higher technology levels.

However, new standards apply to new aircraft, and both Airbus and Boeing have demonstrated a long history of grandfathering in their A320 and 737 product lines. This fact leads to arguing that the application of technology regulations might lead these companies to stretch even more grandfathering in these lines and delay the introduction of new aircraft designs to avoid triggering the standards.

If Airbus and Boeing take a conservative approach, they would choose to maintain their current aircraft to maximize their benefits. However, this tacit alliance could suppose a standstill in technology development, and this could mean a good chance for new competitors to enter the market.

To keep this option under control, it is assumed that technology regulation may force manufacturers to either stop production of older lines, which will imply exiting the market, re-engineer their models or develop a new aircraft within a five years' time frame (i.e. one stage of the valuation model). Exiting the market will be preceded by a phase-in period in which the manufacturer sells its current product lines while replacements are developed, resulting in a limited period of positive exit payoffs. However, none of the companies could afford to exit from the MoM segment, so this option would not be admissible for any of them.

Under equal conditions, both manufacturers will be inclined to harvest their existing product lines while making a minimum investment to meet regulation by re-engineering. However, re-engineering options of 737 MAX line are much more limited than those of A321XRL, pushing Boeing towards the development of the new 797. Although making a new aircraft is not recommendable because it requires a great investment in the short term, it might be the only option if re-engineering is limited or not possible.

The expectation of High Fuel Prices

If high fuel prices are expected, fuel efficiency will be the main market driver. As discussed previously, manufacturers can increase the selling price of a new aircraft with improved fuel consumption performances. It has been estimated that airlines would pay 15% more for an aircraft providing 15%-20% of fuel savings.

Additionally, better fuel efficiency gives manufacturers a competitive advantage to increase market share. Both factors will allow increasing their benefits, but this can only be achieved if they get a more efficient aircraft with great improvements in fuel burn and a considerable reduction of harmful emissions.

Nevertheless, it will be needed a great investment and a high demand for new aircraft to decrease the cost of producing a unit. This could be achieved by working on the learning curve. Expectations of higher demands and increased revenues from a higher sale price could provide the incentive required to shift the equilibrium to a new aircraft for both players. However, if demand does not develop as expected, this can be a risky endeavour.

It must be taken into account whether the game is cooperative or non-cooperative because if the two competitors could share information with each other, both of them could alter the equilibrium. Although Boeing and Airbus have assay some cooperative approaches in the past (as in the initial stages of the superjumbo project), all these initiatives have turned unfruitful in the end. In this game, we have considered strictly a non-cooperative situation. This hypothesis might be altered by other variables such as the entrance of a new competitor in the scenario, but this is not today an alternative for the Middle of the Market.

Airport infrastructure and congestion

One key element threatening aviation growth in the coming years is incapability of ground infrastructure to cope with the growth of rates foreseen and the consequent airport congestions. This scenario has been discussed in detail in 0.

In a scenario of strong economic growth, with a 36% demand increase, by 2050 airport capacity, with incremental improvements in capacity at an annual rate of 0.8% per annum, will soon become a bottleneck and severely limit the traffic growth. Only in Europe, it is expected that in 2035, there will be 20 airports handling more than 150,000 departures a year in the most-likely scenario; a level of traffic currently achieved at 8 airports only. This effect is also expected in the regions with big growth prospects, such as South-Asia, China and India.

It might be adventured that this scenario will favour the exploitation of bigger aircraft in the MoM, favouring the acquisitions of new B797 against its competitor with lower seat capacity.

Development of Low-Cost carriers in the MoM

Low-cost operation in medium/ long haul is still very incipient. Possibilities for further development have been discussed in 0.

In this scenario, we consider a favourable evolution of this operation, in which the percentage of low-cost in the MoM could rise up to 35%, sustained on the analysis performed in 0.

Under this scenario, low-cost carriers, or more conventional airliners but offering a mix operation, will be more inclined to buy the new 797 against its competitor due to its lower operating cost, high fuel efficiency and its capacity to transport more passengers. This hypothesis is translated into the model as an increase in the market share as well as an increase in prices.

In this scenario, an additional effect needs to be considered a new clean-sheet aircraft specifically designed and optimised for this market segment might bring opportunities for new routes that today are not considered economically viable. This effect has already happened with the introduction of 787 in longer routes. Although this effect can be partially reflected in the global MoM forecast, it is considered that the development of the medium-haul low-cost operation will favour an additional increase in traffic and operation.

13.2.13.5 Pay off function

To find the expected competitive equilibriums in the static and dynamic games, an estimation of the payoffs of the players is required. An aircraft program valuation model has been developed, based on assumptions found in the literature and publicly available data.

The purpose of the valuation model is not to determine the exact profits manufacturers can expect to receive, but rather to determine the rank ordering of expected payoffs under different competitive scenarios. To determine the Nash equilibrium of the game, the rank ordering of payoffs is required, not absolute values.

The aircraft program valuation model used to estimate the manufacturers' payoffs has been described in detail in Section 13.2.80. The model is based on the assumption that the objective function of each firm is to maximize the net present value of expected profits at a time t. This is a complex model that integrates specific and detailed sub-models to quantify each of the main parameters influencing the value a manufacturer can obtain from an aircraft. As a kind of summary, we listed hereafter the different sub-models integrated into the aircraft valuation model, although readers are referred to 0 for details, hypotheses and explanation of each of the model components:

- Non-recurring Investments
- Recurring Costs of Production
- Fuel Price Forecast Model
- Aircraft Life-Cycle Cost Analysis
- Aircraft Sale Price
- Production Capacity Constraints and Fixed Costs
- Demand Forecast
- Market Share Model

0 includes also a sensitivity analysis to determine whether the rank ordering of payoffs remains constant for the expected range of input values and to which parameters the model is most sensitive. It allows to estimate the impact that each one of the sub-models and parameters considered has in the final calculation of company profits and to determine whether the aircraft program valuation model is robust.

In this section, it will be applied the aircraft program valuation to the reference scenario, which is the baseline forecast considered in the study. The purpose is showing the application of the complete model to one scenario, explaining in detail each one of its phases as well as providing results.

Application to the reference scenario

The reference scenario is the base case against which the other games that will be analysed in the study are compared to understand how the scenario examined impacts the outcome of the game.

In this scenario, fuel efficiency and aircraft operating costs are differentiating factors which affect airlines decisions. That is, airlines will be willing to pay for aircraft models with the latest fuel efficiency technology, improved engines or lower weight since aircraft with these characteristics provide significant reductions in operating costs. In this way, an aircraft with substantial operational savings can convince airlines to switch to the aircraft's competitor.

This fact encourages manufacturers to invest in more innovative and efficient technologies with the aim of achieving a greater market share and, consequently, more benefits. This is the case of re-engineered versions of existing aircraft, which supposes an economic strategy as it consists of applying modifications to provide superior performance improvement but in general the modified aircraft remains very similar to the original. This procedure implies less risk and capital requirements for manufacturers than developing a new one from the beginning although it offers lower potential fuel burn improvements.

Developing a new clean-sheet aircraft involves a great effort in cost investment and research, being necessary several years to complete the program and launch of the product. In the reference scenario, it is only contemplated the new Boeing NMA as new aircraft program development. For this aircraft, it is required to estimate the non-recurring and recurring costs, which correspond with development and manufacturing phases, respectively. The calculation procedure of this phase is explained in detail in section 13.2.8.1, and Table 13.23 located in section 13.2.8.5 shows the model input parameters used for the Boeing NMA.

The other aircraft that could become potential competitors for the NMA and, consequently, threat its market position are re-engineered versions. However, as most of them are currently in service or are planned to enter in service before 2020, it is not required to calculate the non-recurring costs since it is assumed that manufacturers have already made the development investment. The only for which the re-engineering cost has been estimated is the A321neoXLR, as its introduction is expected around 2025. After reviewing several aircraft cost program with their modified and improved versions, it was estimated that the cost of re-engineering corresponds to 30% of the cost of developing the same aircraft from the beginning.

Once the development and production costs have been analysed, the next step is the calculation of aircraft operational costs as it will be used as a base to obtain market share estimation. These costs, together with the market share, will allow obtaining the quantity of aircraft that are expected to be sold for the Middle of the Market, thanks to the support of the demand forecast performed in 0. Finally, with all the phases which compose the model calculated, it is obtained the Net Present Value for each one of the strategies that manufacturers can choose.

The reference scenario consists of a static game in which both manufactures interact only one time by taking a decision at the beginning of the period of analysis, which is in this case between 2020 to 2040. The consequences of this decision are observed over time. Figure 13.100 shows the possible options or strategies that manufacturers can follow. The explanation about why these strategies have been considered is provided in section 13.2.13.3.

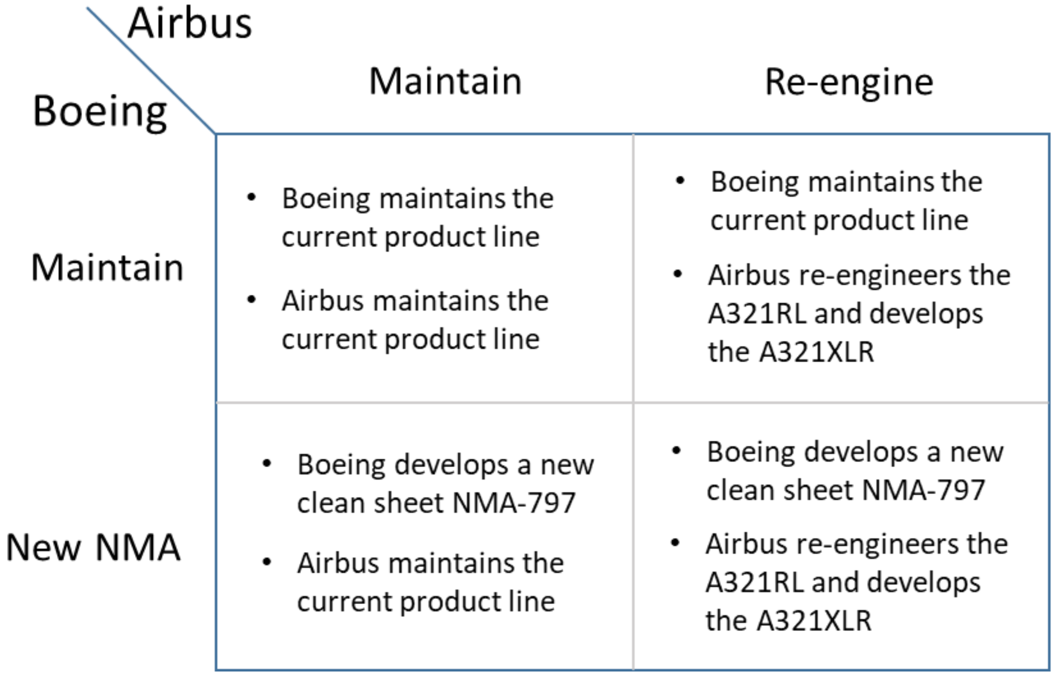


Figure 13.100. Reference scenario possibly strategies

Figure 13.100 illustrates the reference scenario with the strategies to be followed by manufacturers. The market share, as well as NPV, must be estimated for each one of the cases shown in the figure, resulting in a total of four cases of which results are indicated below.

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 62.257– A: 74.810	B:44.326—A: 93.405
Launch NMA	B: 56.192 – A: 46.488	B: 49.724 – A: 54.248

Table 13.27. Reference scenario payoffs

Each one of this scenario is explained in detail in the following sections, providing the assumptions considered, as well as market share estimation results.

Maintain/Maintain strategies case

In this case, along the 2020-2040 period, Boeing maintains the current product line, which is composed of B737 family, B757, B767, B787, B777 and B747. On the other hand, Airbus also maintains its fleet, formed by the following aircraft: A320 family, A330, A380, A340 and A350.

Currently, Boeing is dominating the Middle of the Market with 56% of market share while the remaining 44% is exploited by Airbus models. However, it is expected that this situation changes in the analysed period with the introduction of the stretched version of the A321neo, the A321neoLR, with more range capability.

The B737 MAX family would be the main bet of Boeing to compete against the A320neo family, taking into account their commercial success. The main candidates of these two families are the B737 MAX

8 from Boeing with a maximum range of 3550 nm and the A321neoLR from Airbus with a maximum range of 4000 nm. Although these aircraft are focused on the short-haul market, it is assumed that they will absorb part of the MoM market share due to their great efficiency and reduced operating costs. According to the aircraft program valuation model, these aircraft are significantly superior to the rest of the aircraft considered as potential competitors, which will probably convince airlines to pay for them. Therefore, these two models will absorb together the 80% of the market share, divided equally as there are no relevant differences between them.

This percentage will be reduced gradually by 10% in each segment due to the increase in range, as airlines will be more willing to pay for larger aircraft. In the last segment, located in a range exceeding 4000 nm, the market share is totally absorbed by wide-body aircraft as it surpasses the maximum range of A321LR and MAX 8.

Figure 13.101 shows the market share obtained considering all the previous assumptions. It indicates that the market is split between narrow-bodies and wide-bodies, each one with around 50% of the market share. However, due to the substantial improvements provided by 737 MAX and A320neo families as well as the necessary replacement of old fleet, a great market share is absorbed by these models if it is not expected a new competitive entrant that can change the situation. On the other hand, as A321neo LR possess a higher range than the 737 MAX, it will achieve more market share percentage for longer routes.

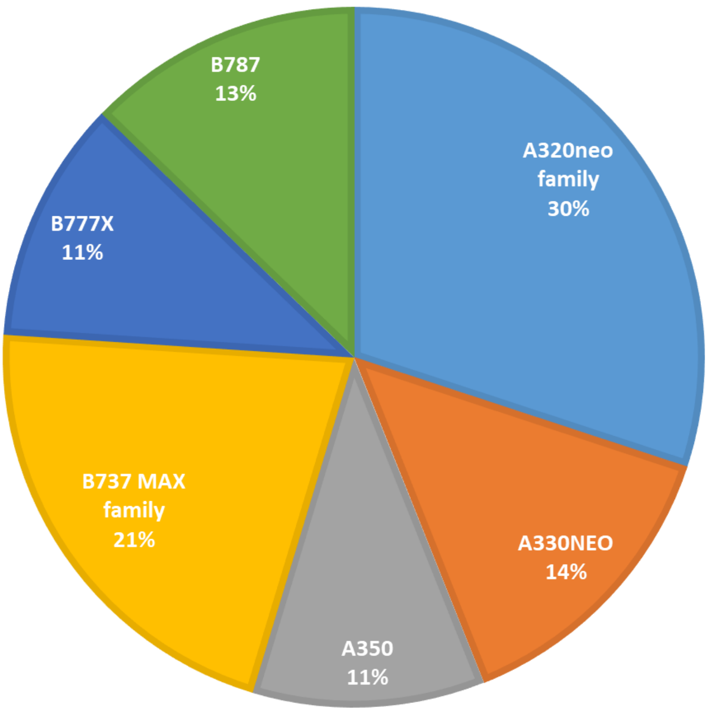


Figure 13.101. Market share by model for the 2020-2040 period for the strategy Maintain/Maintain

Taking as a base the market share by the model shown in the previous figure, below it is shown how the market share will result in distributing it by the manufacturer. As can be seen, Boeing's current domination of MoM would be lost, coming out Airbus as the winner of the competition. That is, the current situation would be reversed in 2040, changing the market share of Boeing from 56% to 45%, which indicates that Boeing should make a decision if it does not want to be surpassed by Airbus.

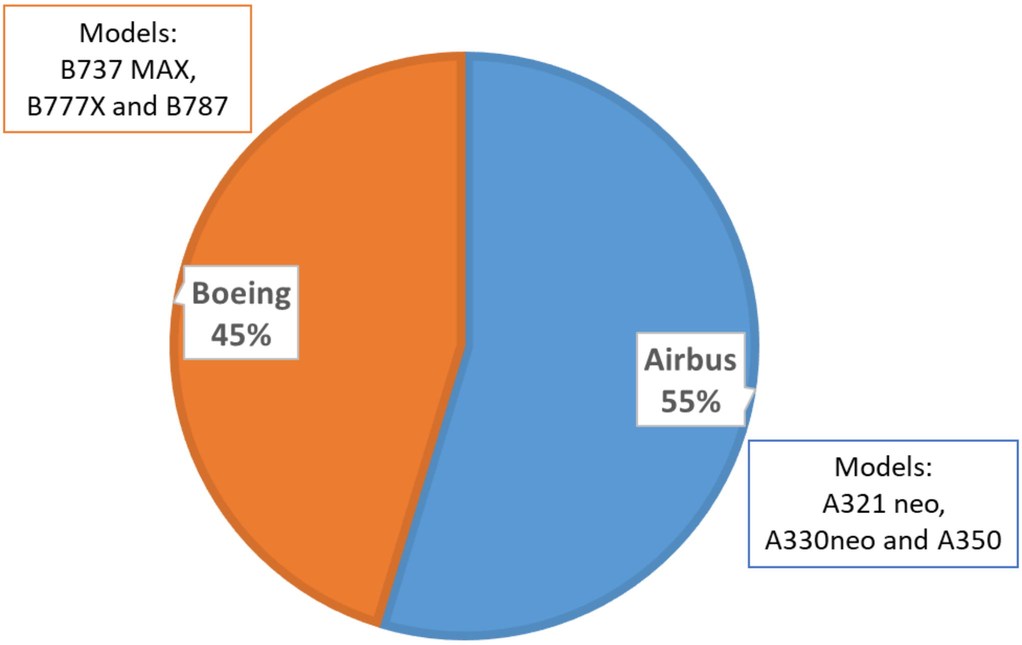


Figure 13.102. Market share by the manufacturer for the 2020-2040 period for the strategy Maintain-Maintain

With the market share shown in Figure 13.101, it is calculated the number of deliveries to be produced of each aircraft to satisfy the market demand. These deliveries are used as inputs in the Net Present Value calculation, providing the final results shown in Table 13.27 included before.

Maintain/Re-engine strategies case

In this case, along the 2020-2040 period, Boeing maintains the current product line, which is composed of B737 family, B757, B767, B787, B777 and B747. On the other hand, Airbus takes the decision of extending the A321LR range capabilities, resulting in a re-engineered version called A321XLR. This decision would be taken in 2020 but the new A321XLR program would not enter service before 2025, which will affect payoff estimation.

As this model is a re-engineered version and not a new aircraft development, the non-recurring costs will be quite lower, around 30% of the cost of developing the same aircraft from the beginning. This fact will allow Airbus to gain great benefits without the investment and effort required to develop a new aircraft from scratch.

It is assumed that this model will be a little more efficient than the current A321LR thanks to engine improvements as well as more passenger's capacity which will provide better fuel burn consumption. Additionally, it will have more range than its previous version due to the incorporation of an additional fuel tank that will allow it to fly up to 4700 nm. With this aircraft, Airbus will pursue to control the MoM segment with the main objective of replacing the B757/B767 fleet, which are very aged models with a significant market share in this segment.

Therefore, in this case, the main candidates to compete in the MoM segment will be the B737 MAX 8 from Boeing and the A321XLR from Airbus, absorbing together the 80% of the market share since they are significantly superior to the rest of the aircraft considered in the study. However, this market share will not be equally distributed for both models as in the maintain-maintain case explained before, because it is expected that the B737 MAX 8 will have less capacity, range and efficiency than its competitor, resulting in a 10% reduction of market share in favour of the A321XLR.

In addition, in the same way, as in the previous case, this percentage will be reduced gradually a 10% in each segment due to the increase in range, as airlines will be more willing to pay for larger aircraft. However, in the last segment, located in a range exceeding 4000 nm, the A321XLR will also be an important competitor to be considered against wide-bodies due to its efficiency and increased range capabilities.

Figure 13.103 shows the market share obtained considering all the previous assumptions, in which it can be seen the clear advantage of the A321XLR model due to its performance and considering fleet replacement as a market driver. It will absorb a great market if there is not a new entrant which can be a threat thanks to its competitiveness within these routes.

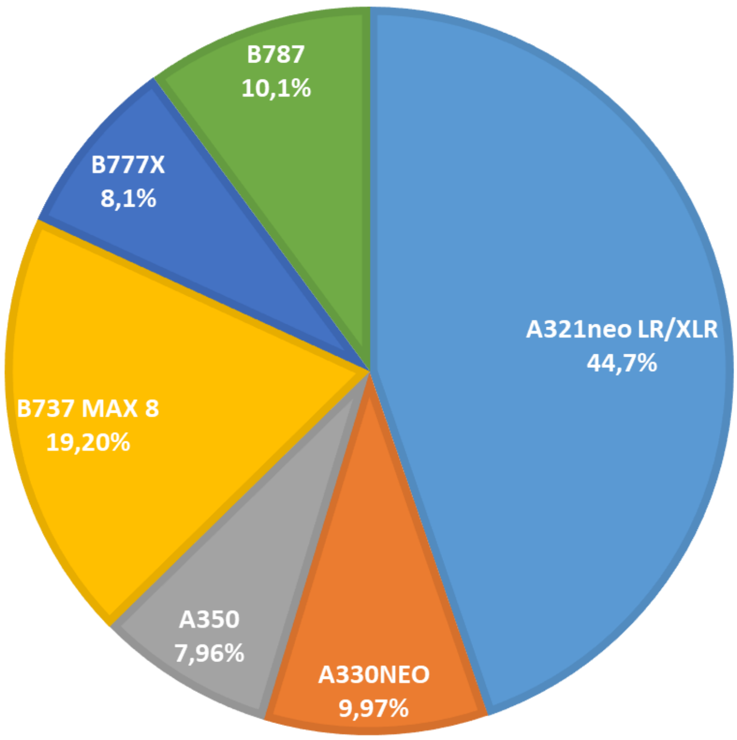


Figure 13.103. Market share by model for the 2020-2040 period for the strategy Maintain/Re-engine

If this case takes place, Boeing will be in a critical situation, because despite dominating the market today, if it does not take a course of action, the new A321XLR will change completely the situation by the year 2040, achieving Airbus a market share of 63%, a great advantage that will become it in the clear leader of the MoM segment.

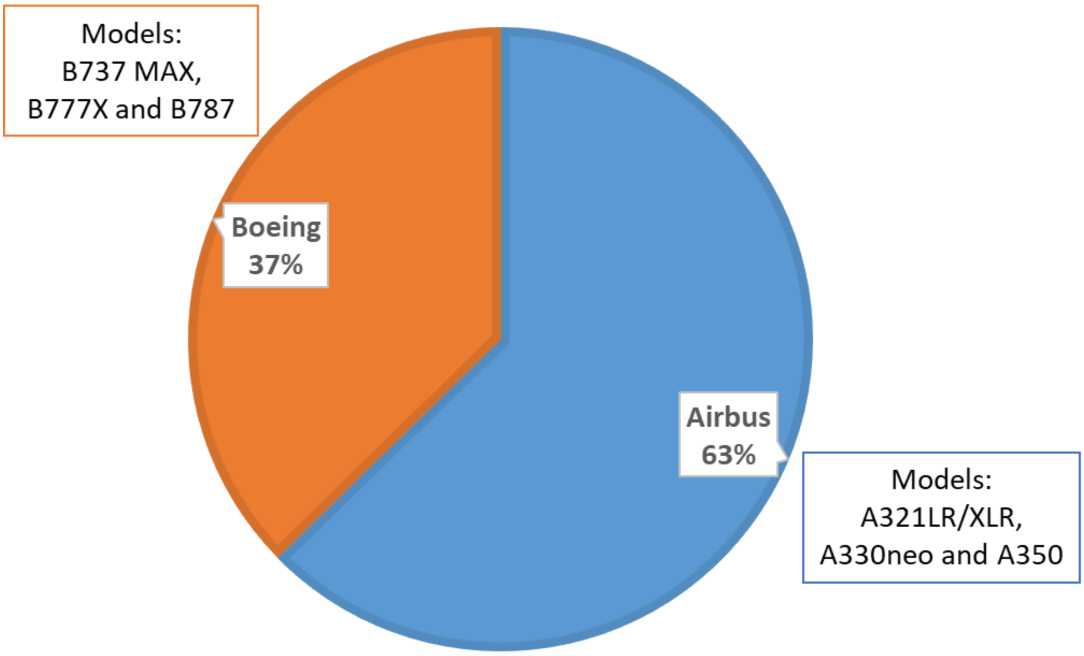


Figure 13.104. Market share by the manufacturer for the 2020-2040 period for the strategy Maintain/Re-engine

With the market share obtained, it is calculated the number of deliveries to be produced of each aircraft to satisfy the market demand. These deliveries are used as inputs in the Net Present Value calculation, providing the final results shown in Table 13.27 included before.

New NMA/Maintain strategies case

In this case, along the 2020-2040 period, Boeing takes the decision of developing a new clean-sheet aircraft model, the B797, but the new program would not enter in service before 2025, On the other hand, Airbus maintains its fleet, formed by the following aircraft: A320 family, A330, A380, A340 and A350.

It is expected that the B797 will incorporate advanced technologies, which will provide significant improvements in terms of weight, fuel efficiency, operational costs, etc. However, developing an aircraft from the beginning requires great investment, being necessary several years to recover the investment made. In addition, if the demand is lower than expected, the investment may not be recovered.

As it was said before, for this aircraft it is necessary to calculate the development and production costs, for which the input parameters introduced in the model are included in section 13.2.8.5. According to the data provided by the aircraft program valuation model, the B797 is significantly more efficient than the other wide-bodies considered in the study, as it will be an aircraft optimised for medium-haul routes. However, single-aisle aircraft such as the B737 MAX 8 or A321LR will be more efficient and economical for shorter distances as they are smaller models.

Therefore, in this case, Boeing would dispose of two candidates to face Airbus current product line, in which the A321LR is the main threat. These three aircraft would absorb together the 80% of the market since they are significantly superior to the rest of the aircraft considered in the study, but it is assigned less percentage to the B797 as it is not as efficient as its single-aisle competitors in shorter distances.

However, as range increases, this model will absorb a great market share since it has been designed for longer routes.

In addition, the market share percentage of A321LR and B737 MAX 8 will be reduced gradually 10% in each segment due to the increase in range. In this way, not only the B797 is favoured but also other wide bodies as companies will be more willing to pay for larger aircraft.

Figure 13.105 shows the market share obtained, which indicates that the B797 will achieve a significant market share, even surpassing the A321LR. This result is especially caused by the replacement of the aged fleet, mostly the B757/767 models. The B797 will absorb a great market share from these models as it is designed to substitute them. If Airbus does not introduce another model which can be competitive for longer routes, airliners will choose to buy the B797 due to its higher range and efficient performance.

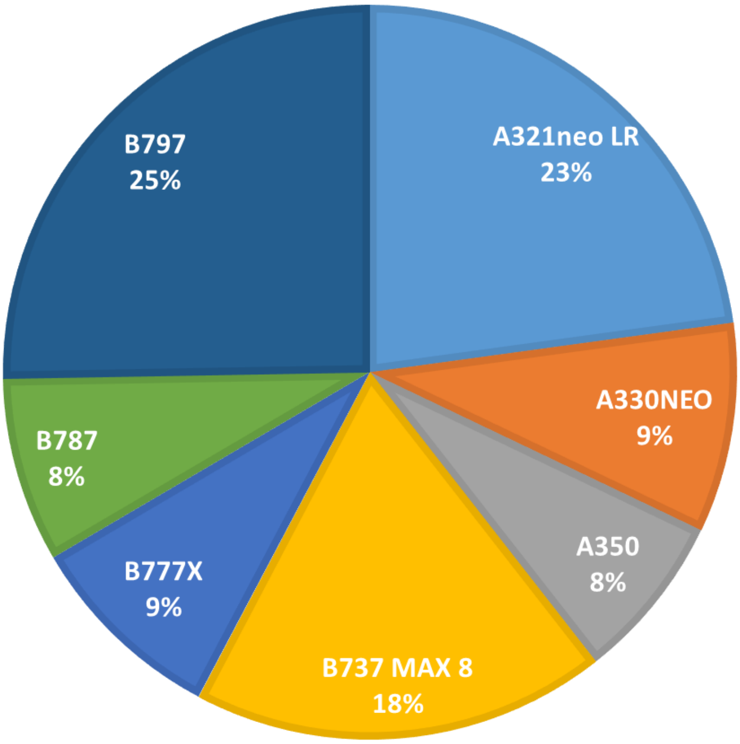


Figure 13.105. Market share by model for the 2020-2040 period for the strategy New NMA/Maintain

With the introduction of new aircraft development, the position of Boeing will be much more advantaged, with a 61% of the market share while Airbus will lose its dominance down to a 39% of market share. Therefore, in this case, Airbus would be in a critical situation and it should take the initiative in order to achieve the MoM segment leadership.

It is important to note that, despite the dominating position of Boeing in the market share, its benefits would not be so high due to the investment required to develop the new aircraft. This fact is shown in NPV estimation, in which there is not a substantial difference between Boeing and Airbus payoffs. Even so, Boeing should follow this path to maintain MoM market position against Airbus.

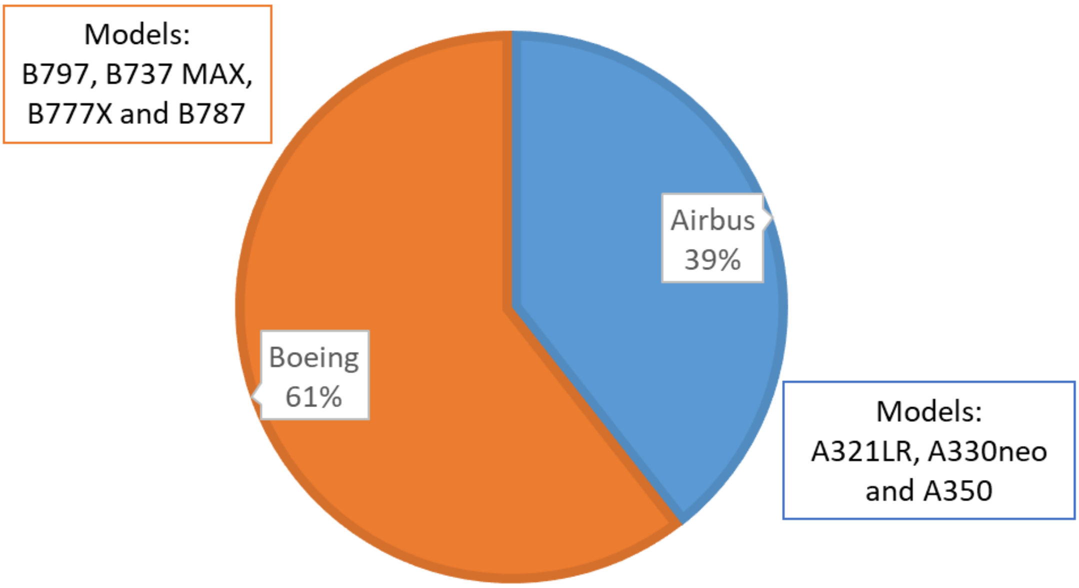


Figure 13.106. Market share by the manufacturer for the 2020-2040 period for the strategy New NMA/Maintain

With the market share obtained, it is calculated the number of deliveries to be produced of each aircraft to satisfy the market demand. These deliveries are used as inputs in the Net Present Value calculation, providing the final results shown Table 13.27 included before.

New NMA/Re-engine

In this case, along the 2020-2040 period, Boeing takes the decision of developing a new clean-sheet aircraft model, the B797, but the new program would not enter in service before 2025, On the other hand, Airbus takes the decision of extending the A321LR range capabilities, resulting in a re-engineered version called A321XLR. This decision would be taken in 2020 but the new A321XLR program would not enter service before 2025.

In this case, the A321LR and A321XLR will be the main candidates to compete against Boeing products, the B797 as well as the B737 MAX 8. All these aircraft together would absorb 80% of the market. In addition, it is assigned a 10% more of the percentage to the A321LR/XLR variants, as they will be very efficient models at shorter distances.

As range increases, the B797 market share percentage will also increase since it has been designed for longer routes. However, in this case, the percentage will not be as high as in the New NMA/Maintain strategy, as the A321XLR will be a significant threat due to increased range capabilities.

On the other side, the market share percentage of the previous models mentioned will be also reduced gradually 10% in each segment due to the increase in range. In this way, not only the B797 will be favoured but also other wide bodies as companies will be more willing to pay for larger aircraft.

Figure 13.107 shows the market share obtained, which indicates that the B797 will achieve a significant market share, but not as high as in the previous scenario. The A321LR and A321XLR will be the most successful models, which will allow Airbus to obtain significant benefits as these variants do not require a great investment compared to new aircraft development. In any case, the B797 will also absorb a significant market, allowing Boeing not to lose the dominance of the market.

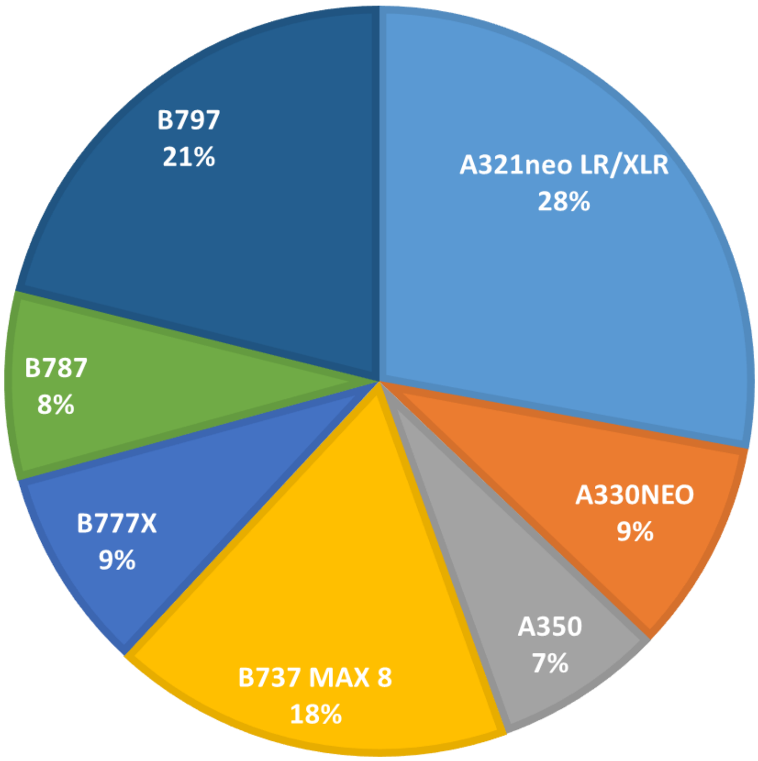


Figure 13.107. Market share by model for the 2020-2040 period for the strategy New NMA/Re-engine

In terms of total market share, Boeing would be the leader of the MoM segment thanks to the introduction of the B797, achieving a 55% of market share (Figure 13.108). However, due to the high investment required for its development, the NPV values obtained are very similar to Airbus benefits. This fact indicates that Airbus position in the Middle of the Market is very advantaged, as it would only lose significantly against Boeing in the New/Maintain strategy scenario.

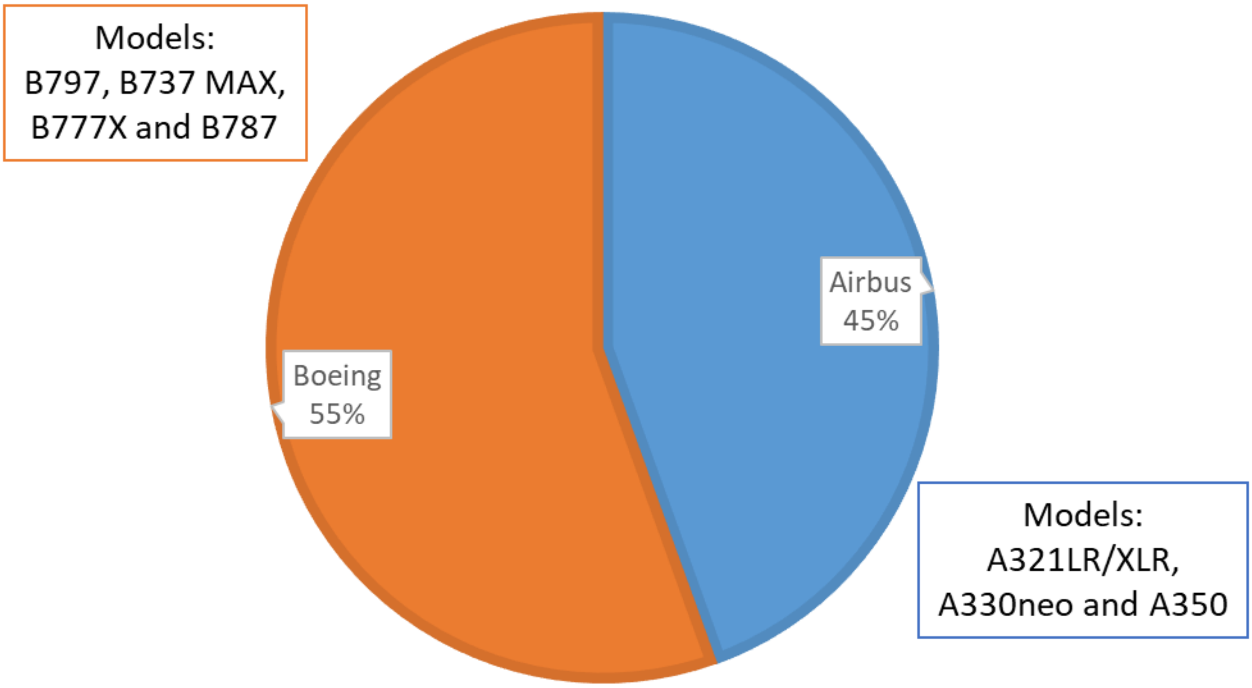


Figure 13.108. Market share by the manufacturer for the 2020-2040 period for the strategy New NMA/Re-engine

With the market share obtained, it is calculated the number of deliveries to be produced of each aircraft to satisfy the market demand. These deliveries are used as inputs in the Net Present Value calculation, providing the final results shown Table 13.27 included before.

13.2.14 Game theory analysis of the MMA competition

In this chapter, the study of the different scenarios explained in section 13.2.13.4 will be carried out generating results for each game, analysing first the static games and later the dynamic games.

The results of the research have been analysed using two different tools, Gambit software and Game Theory Explorer GTE. The results obtained using both tools coincide. The Gambit tool is used to analyse the static games while the dynamic ones will be carried out by its online version, using in this way both tools.

The whole process and the detailed analysis are explained for the reference scenario, which can be found in the Annexes. In this chapter, it will be provided with the static and dynamic game analysis results for each game and also the specific hypotheses and conclusions.

13.2.14.1 Static games

In this section, the analysis of static games for the different scenarios proposed in the study will be carried out. It has to be taken into account that both manufacturers make their decision at the same time, at the beginning of the established period to be analysed.

In addition, the strategies considered, which have been outlined in 0 and 13.2.13, are the same for each static game.

The decisions made by both manufacturers, Boeing and Airbus, will be analysed in order to obtain the most optimal combination of strategies, that is, the Nash equilibrium. In the following tables, the solution of the strategic problem, that is, the Nash equilibrium is indicated in yellow colour for each static game.

Reference scenario

The reference scenario consists of a static game in which both manufactures interact only one time by taking a decision at the beginning of the period of analysis, which is in this case between 2020 to 2040. The consequences of this decision are observed over time.

The hypothesis and dynamics in the reference scenario have been fully detailed in section 13.2.13.5 "Application to the reference scenario". Market share heuristics were discussed in section 13.2.8.3 and summarised in Table 13.20.

The market share, as well as NPV, must be estimated for each one of the cases, resulting in a total of four cases of which results would be indicated below.

The main hypotheses applied for this scenario are the following ones:

- Two or more aircraft with significant cost improvements would get a maximum of 80% of the market share.
- The market share of A320 and B737 families are completely absorbed by their newest versions, the A321neoLR and B737 MAX 8
- No significant differences in cost efficiency among aircraft mean that market share is equally distributed.
- To distribute the market share of an aircraft, it will be assigned more percentage to the same manufacturer models, a minimum of 5%.
- It will be assigned more market share percentage to those aircraft which are re-engine versions when the market share of previous models is distributed
- A percentage will be added as the range segment increases in favour of larger aircraft
- A percentage of loyalty is assigned to the models A350 and B787
- As B757/B767 fleet is expected to be retired in the following years, their market must be distributed. It will be assigned more percentage to the new Boeing airplane, the B797, as it will be designed specifically to replace this fleet

Once the hypotheses have been outlined, it is going to be explained how the market share in terms of airplanes would be distributed and how it would change depending on the different strategies followed by manufacturers.

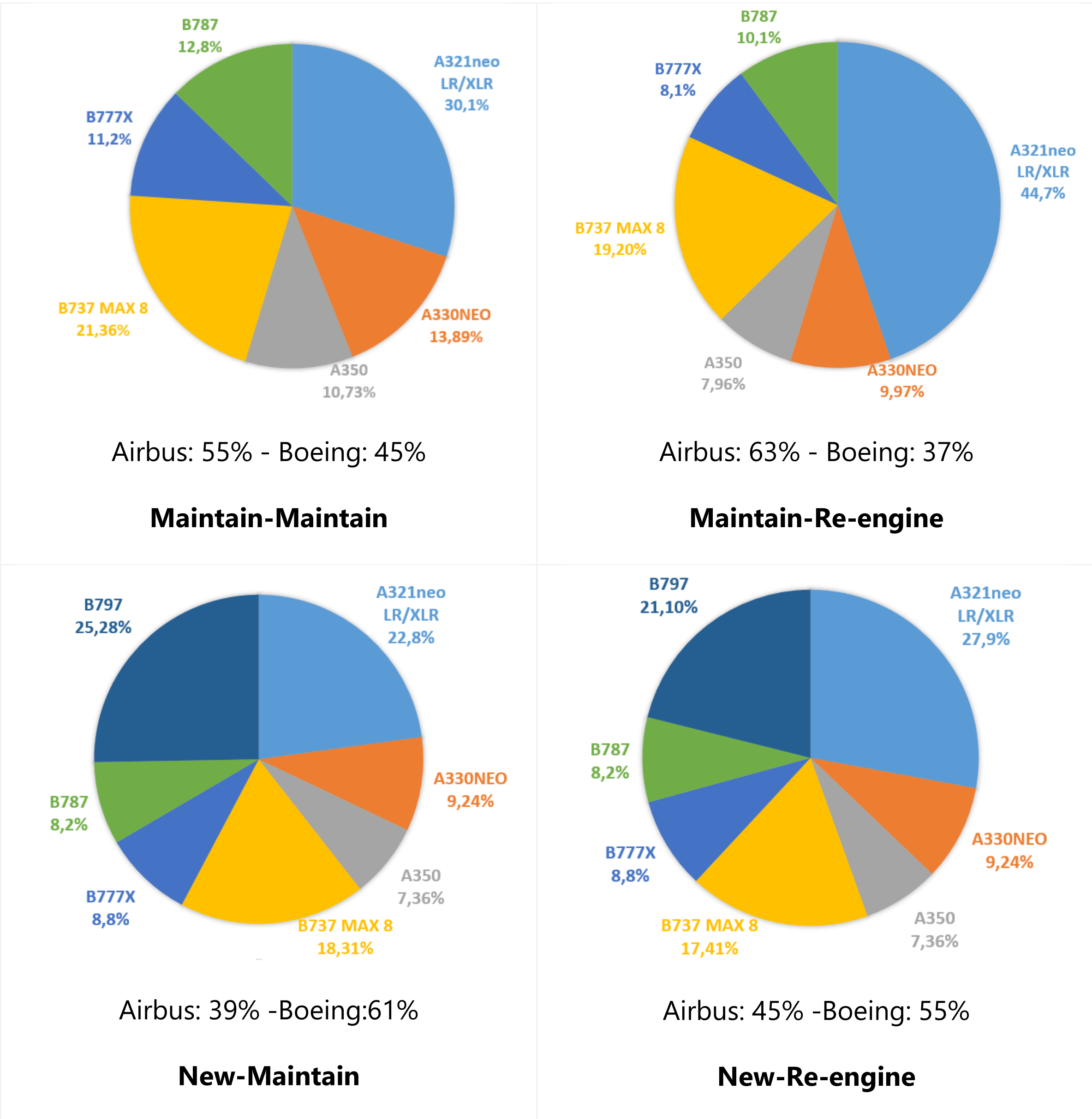


Figure 13.109. The market share reference scenario

As it can be seen in Figure 13.109, in terms of airplanes market share, the market will be mainly divided into 3 models corresponding to B797, A321neoLR and B737 MAX 8.

Using software tools mentioned before, Nash equilibrium will be reached if Airbus decides to make re-engineering and Boeing decides to launch a new aircraft. The game analysis would result in Boeing deciding to invest capital in the incorporation of a new aircraft to the market, the B797, trying to fill the gap that Boeing has for this segment. Airbus is going to bet for making the re-engineering of its model A321LR making it more competitive to try to dominate the MoM. The following table shows the payoff manufacturers will obtain for each combination of strategies and highlights in yellow the Nash equilibrium:

Boeing\Airbus	Maintain	Re-eng. A321XLR
Maintain	B: 62– A: 75	B:44—A: 93
Launch NMA	B: 56 – A: 46	B: 50 – A: 54

Table 13.28. Reference scenario payoffs

In this scenario, the returns are higher for Airbus than for Boeing. The reason why Airbus' payoffs are greater than that obtained by Boeing is due to a combination between the forecast results of the market share percentage they will have in the future and the investment required to change strategy, which will be lower for Airbus than for Boeing.

Both players have the incentive to oust their competitor in the MoM market by changing their strategy, but the situation is somewhat more critical for Boeing, because, in the case of this one, it makes no sense to make re-engineering, as it will not achieve a sufficient market share to compete with Airbus according to forecasts.

Therefore, changing its strategy towards developing a new aircraft model is its only option to gain a significant market share. However, Airbus will change its strategy towards re-engineering to gain greater market share as shown by Nash Equilibrium "New-Re-engine".

The position of Airbus will always be more advantageous when changing strategy, since the investment needed to do re-engineering is not very high compared to the investment involved in developing a new model of aircraft. This is the main reason which explains that Airbus' payoffs are higher than Boeing's payoffs in the equilibrium situation.

On the other hand, if both manufacturers make an agreement in order to maintain their current aircraft, they would be able to take advantage of their current fleet, optimizing the usage of the aircraft they already possess, which have been sold really well so both manufacturers would get the greatest payoffs possible. This situation of tacit agreement between Airbus and Boeing would be the most attractive to achieve the maximum profits, but it could lead to a stagnation of the technology which can result in a slowdown of the investment, so it could not be a situation of sustainable balance in the long term.

The result of the game shows that the situation in which both choose the option of maintaining their current aircraft is not an equilibrium situation, what is more, Boeing would be the most disadvantaged in the long run, as it will result in a large loss of market share absorbed by Airbus.

The expectation of Low Fuel Prices.

In this scenario, the following hypotheses have been considered:

- In this case, fuel efficiency is not a differentiating factor to impact airlines decision. Therefore, the market share of the most efficient aircraft is reduced gradually by 20% in each range segment. This will benefit larger aircraft, which exhibit lower fuel efficient for shorter ranges.
- The market will be distributed equally between aircraft with similar fuel and operational efficiency.

The resulting market share is presented in Figure 13.110.

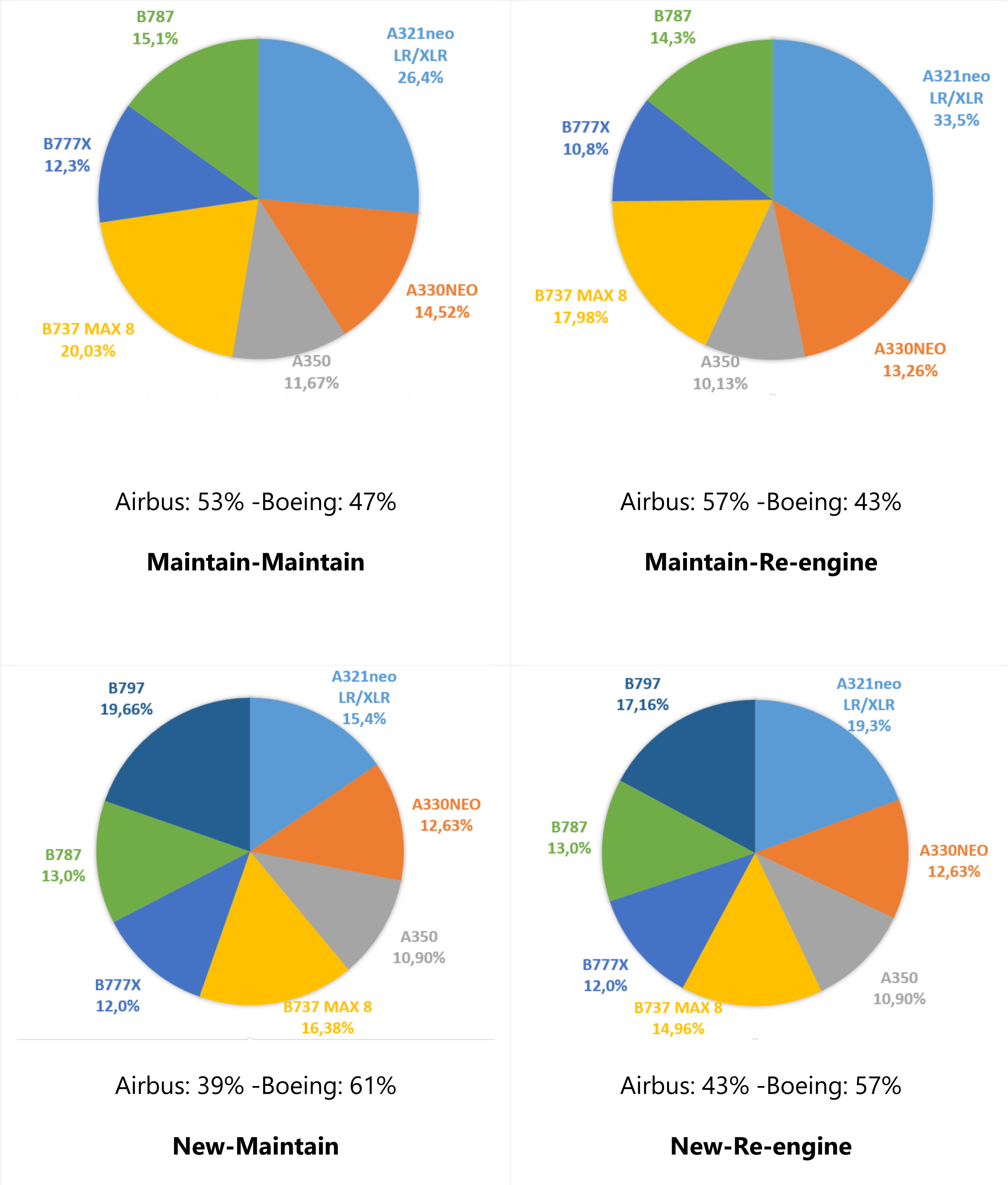


Figure 13.110.Market share low fuel prices scenario

As can be seen in Figure 13.110, in terms of airplanes market share, the market will be mainly dominated by the A321LR/XLR, obtaining a great percentage in comparison to the rest of the airplanes, which have a similar market share.

In the low fuel prices scenario, as it is seen in

Table

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 64– A: 66	B:52—A: 79
Launch NMA	B: 56 – A: 42	B: 47 – A: 47

13.29, there is a Nash Equilibrium when Boeing decides to maintain its products line of the 737 MAX family, and Airbus decides to invest part of its capital in re-engineering to carry out the development of the A321XLR, gaining a significant market share.

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 64– A: 66	B:52—A: 79
Launch NMA	B: 56 – A: 42	B: 47 – A: 47

Table 13.29. The expectation of low fuel prices payoffs

The main incentive to develop a new clean-sheet design aircraft with improvements in efficiency and performance is to gain greater market share, and therefore to obtain a better position in the MoM by achieving better profits than the rest of competitors. In this case, the equilibrium situation will change compared to the reference scenario. Fuel-burning efficiency will not be the main factor for airlines to decide when buying an aircraft. The elevated cost of developing a new more efficient aircraft will not be recompensed in this scenario with higher selling and higher market share. Market share of the most efficient aircraft is reduced by 20% in each range segment, which will benefit larger aircraft over smaller ones. Larger aircraft will carry more passengers, and because fuel price is low, operation cost will be contained.

In this scenario, the Nash equilibrium situation shows that neither Boeing nor Airbus will have a sufficient incentive to made big investment in fuel efficiency technologies. However, it can be seen that in this equilibrium situation, Airbus will get greater benefits from the decision to re-engineer its A321XLR model, while Boeing will remain still competitive by maintaining its current airplanes. It is assumed that Boeing will not be able to sell enough number of aircraft to compensate for the high development cost of the new aircraft, even if it turns out to be more efficient. Boeing's investment will be riskier because it is too high. Whereas Airbus will not need high investment to do re-engineering and the profit would be enough even if its market share is not so important as in the reference scenario.

The expectation of High Fuel Prices.

In this scenario, the following hypotheses have been considered:

- The set of most efficient aircraft absorbs a maximum a market share of 90% at the lower range band. Share decreases by 5% in each range segment.
- In this case, the maximum market share that can absorb a single aircraft is 60%.
- Due to the increase in fuel prices, improvements in fuel efficiency become an essential factor. Therefore, manufacturers can increase price sale as these improvements can provide significant operational savings. Customers will accept to pay more and the price increase will be proportional to the expected reduction in operational cost. It has been assumed an increase of 15% in price sale.

The resulting market share for the period 2020-2040 is presented in Figure 13.111.

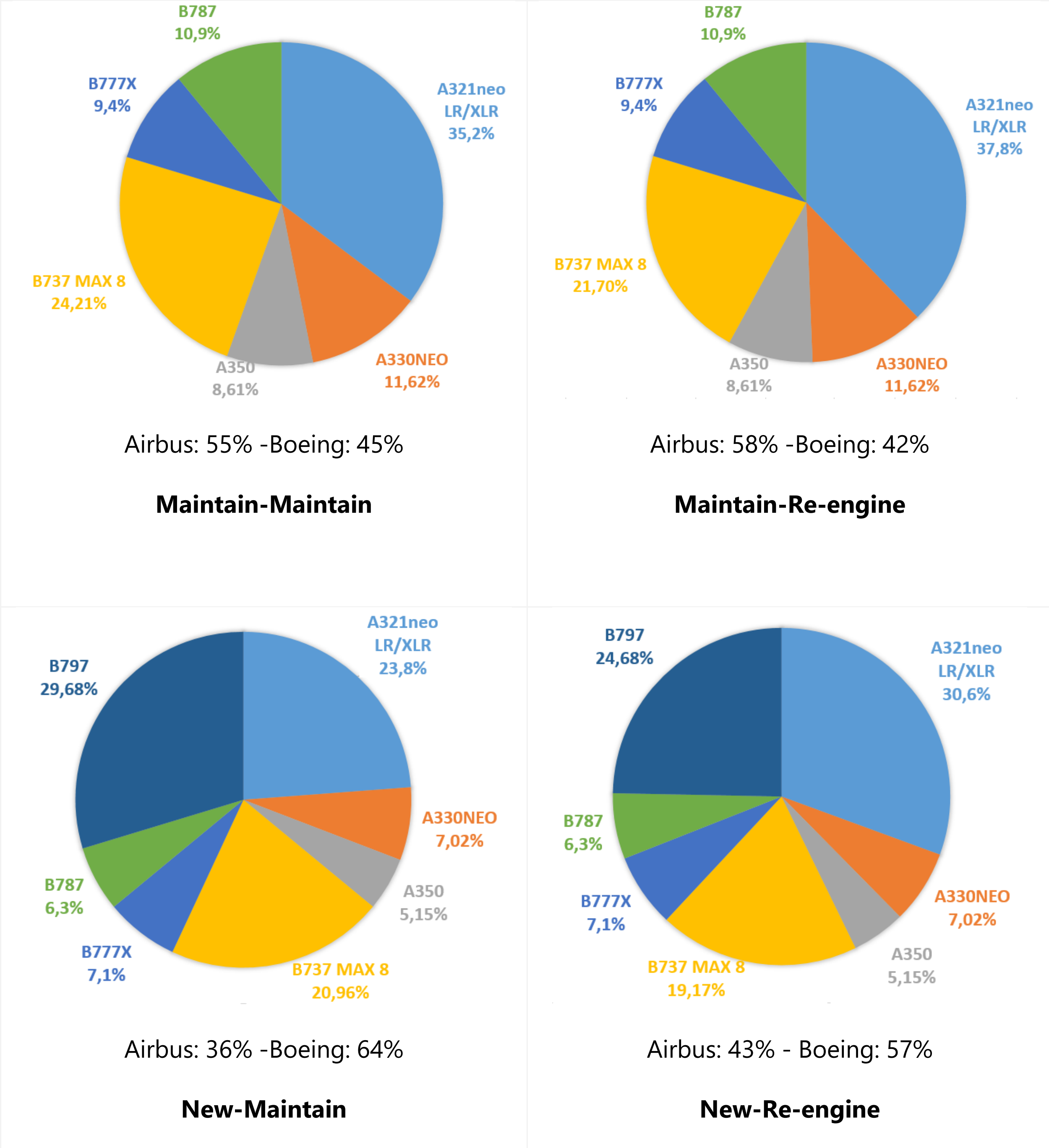


Figure 13.111. Market share High fuel prices scenario

As can be seen in Figure 13.111, in terms of airplanes market share, the market will be mainly dominated by the A321LR, B797 and B737MAX 8. The rest of the airplanes have a little market share percentage.

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 94– A: 115	B:85—A: 122
Launch NMA	B: 130 – A: 70	B: 102 – A: 88

Table 13.30. The expectation of high fuel prices payoffs

Nash equilibrium is reached if Airbus decides to re-engineer its A321XLR model and Boeing decides to launch a new MoM aircraft.

Due to the increase in the fuel price, efficiency improvements will be the main factor influencing manufacturers' decision. Manufacturers can increase the sales price of the aircraft in proportion to the savings obtained from improvements in efficiency and operating costs. It is assumed that airlines accept to pay an additional 15% for this kind of aircraft if these improvements are indeed capable of significantly reducing operating costs.

In this case, Boeing would benefit more than its competitor if it manages to launch its new aircraft on time, which is much more efficient in terms of fuel burn than the possible re-engineered Airbus model. There will be high demand for this new aircraft, allowing Boeing to increase its selling price, thus increasing its profits by a greater proportion than for Airbus.

Increase in Airport Congestion.

In this scenario, the following hypotheses have been considered:

- The market share is reduced a 5% additional compared to the reference scenario in each segment to favour larger aircraft.
- In addition, market share absorbed by the B797 is increased a10%, as its capacity is higher compared to the A321LR.
- The market share of the A321XLR remains identical, as its capacity is the same as A321LR.
- Compared to the B737 MAX 8, the A321LR/XLR is a little larger. For this reason, it absorbs 5% more.

The resulting market share for the period 2020-2040 is presented in Figure 13.112.

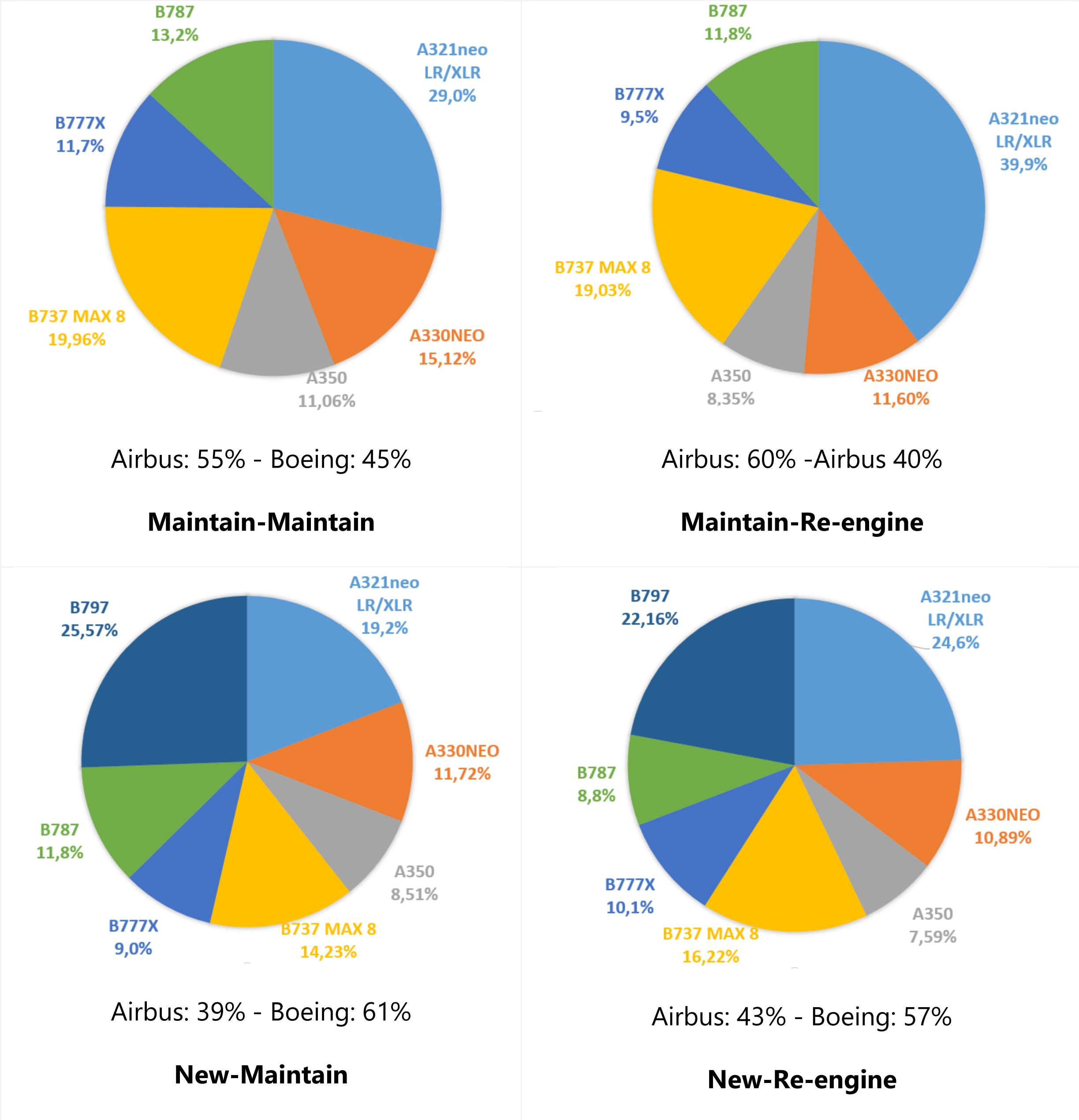


Figure 13.112. Market share congestion scenario

As can be seen in Figure 13.112, the market will be mainly dominated by the new models of these manufacturers such as the A321LR and B797. The rest of the airplanes have a similar distribution; except for the B737 MAX 8 which has more market share.

In this scenario, as can be seen in Table 13.31, Nash equilibrium is reached if Boeing decides to bet on the development of a new aircraft and Airbus decides to develop the A321XLR.

Boeing/Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 59– A: 73	B:48—A: 86
Launch NMA	B: 51 – A: 50	B: 53 – A: 50

Table 13.31. Airport congestion payoffs

Under a scenario of increasing airport congestion and increasing air traffic, the trend of balance will benefit larger aircraft with more seats and a wider range, because with the same number of flights, they would be able to transport a higher volume of passengers, and they will also be able to offer lower operating costs.

The Nash equilibrium shows that Airbus will opt for re-engineering, in order to extend its A321XLR model so that it has more capacity and can transport more passengers. On the other hand, in order to reach an equilibrium, Boeing is expected to opt for the development of a new aircraft with a large number of seats in order to compete against Airbus.

It is assumed that fuel price is the same as in the reference scenario, however, the market share model will largely favour larger aircraft over smaller ones. The market share of the B797 model will increase by 10% because it has a higher capacity than its Airbus competitor, the A321LR. It could be said that in this scenario the operation of larger planes within the MoM segment will be favoured, allowing Boeing to obtain greater sells and payoffs than Airbus.

Development of low-cost carriers in the MoM sector.

In this scenario, the following hypotheses have been considered:

- Low-cost can increase up to 35% for the Middle of the Market in 2040. This 35% will mostly choose the A321LR and B737 MAX 8.
- The rest of the market (65%) is distributed in the same way as in the reference scenario.

The resulting market share for the period 2020-2040 is presented in Figure 13.113.

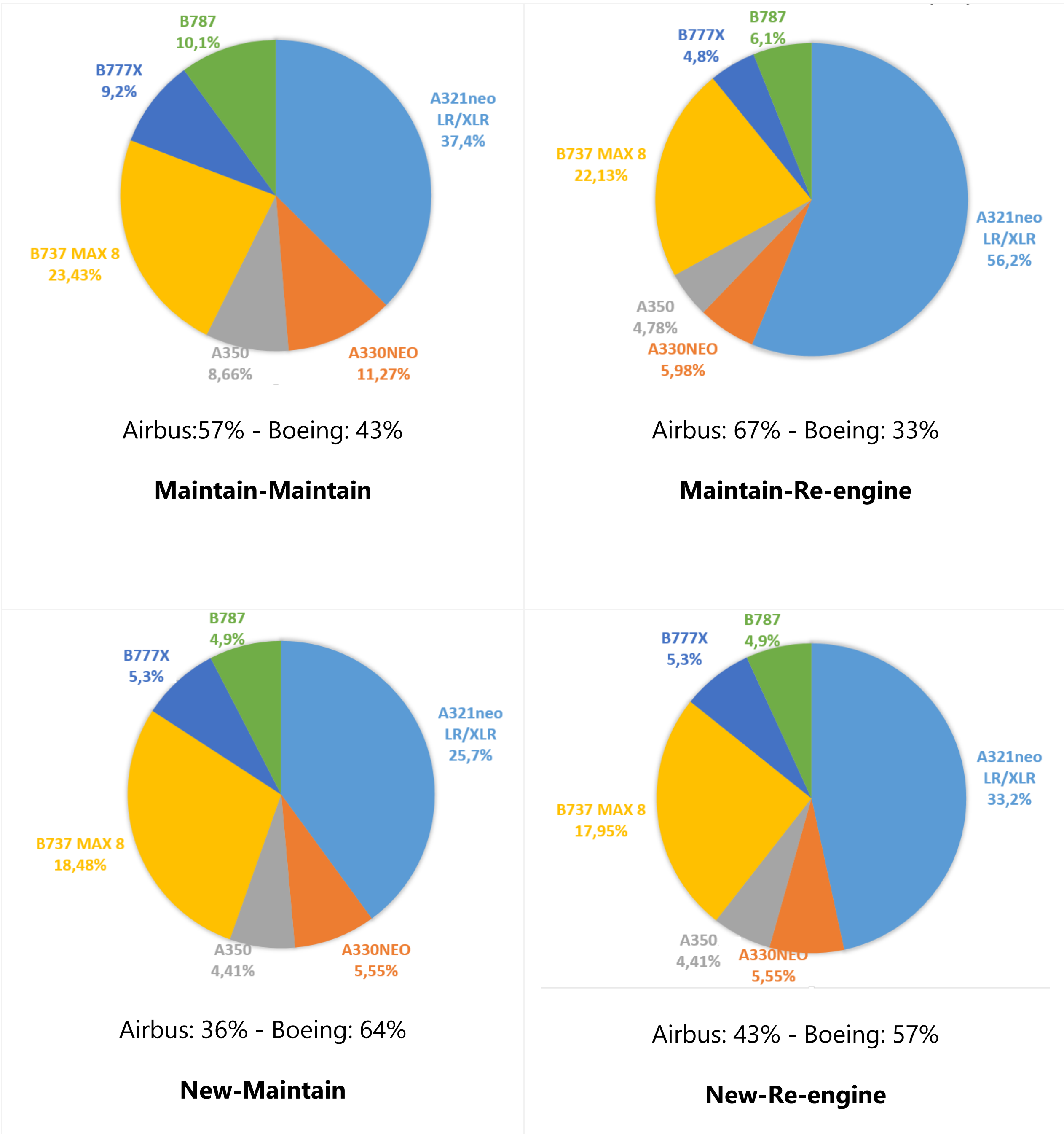


Figure 13.113. Market share Low-cost scenario

As can be seen in Figure 13.113, the market will be mainly dominated by the new model of Airbus, the A321LR. The rest of the airplanes have similar market share except for the B737 MAX 8 which has a percentage of 17,95%.

Nash equilibrium in this scenario comes when Boeing decides to launch a new NMA aircraft, which is really efficient to justify its purchase from low-cost companies. Therefore, it is assumed that this new model and its operating cost would be reduced by a significant percentage, as the technology used would be inherited from other models, which would result in lower tickets for passengers and low-cost airlines could further optimize this model. As for Airbus, they will decide to bet on re-engineering. This decision will bring the two manufacturers to the optimal point.

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 57– A: 84	B:44—A: 115
Launch NMA	B: 68 – A: 46	B: 59 – A: 59

Table 13.32. Low-costs scenario payoffs

In this scenario, it is expected that by 2040 there will be a great development of operation within the MoM by low-cost airlines. The manufacturer which delivers an aircraft with great capacity, that consumes little fuel and also has an affordable price, will be the model most demanded by low-cost airlines in the MoM. Efficient aircraft are expected to be the most demanded, such as the A321LR, B737 MAX8 and B797. It has been assumed that 60 % of the market will be split equally among the most efficient aircraft, as in the reference scenario. The remaining 40% of the market will be divided differently between Airbus and Boeing so that the new B797 will take 55% and the A321XLR model 45% thanks to the re-engineering.

In this Nash equilibrium, the payoffs are the same for Boeing as for Airbus, so one can assume that under this scenario, the two competitors would benefit equally. This means that low-cost airlines will purchase aircraft from both manufacturers without distinction.

Technology Forcing Regulations Scenario

In this scenario, the following hypotheses have been considered:

- The market share remains identical to the reference scenario, but in this case, the non-recurring costs, which are related to research and development, increase 20%.

The resulting market share for the period 2020-2040 is presented in Figure 13.114.

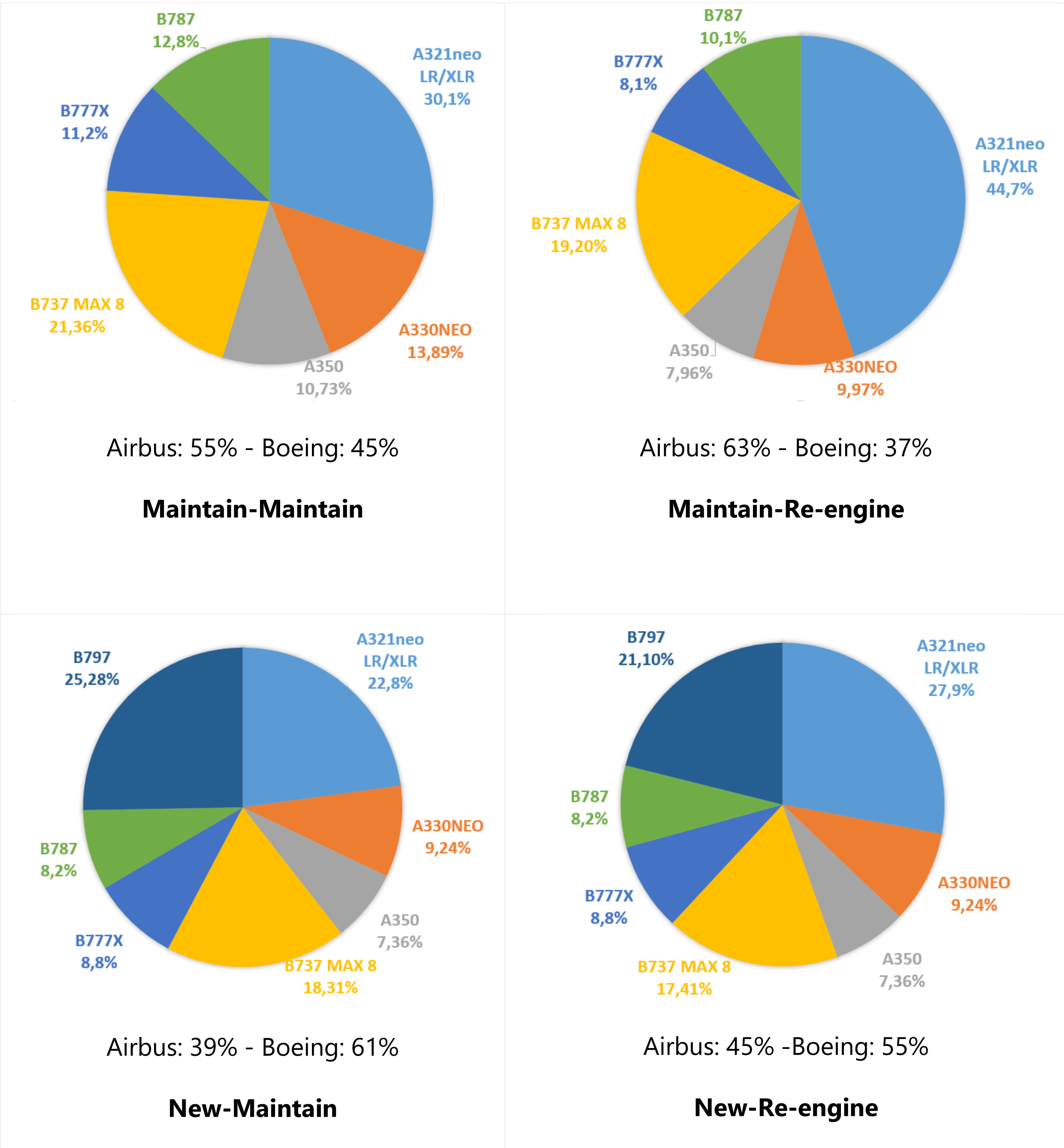


Figure 13.114. Market share Technology forcing regulations scenario

As can be seen in Figure 13.114, the market will be distributed among the following models: B797, B737MAX 8 and A321neoLR. The rest of the airplanes have a similar market share.

In this scenario, Nash equilibrium is reached when Boeing decides to bet on releasing a new aircraft and Airbus bets on the re-engineering, as can be seen in

Boeing\Airbus	Maintain	Re-eng. A321XLR
Maintain	B: 62.257– A: 74.810	B:44.326—A: 92.805
Launch NMA	B: 53.792 – A: 46.488	B: 47.324 – A: 54.248

Table 13.33.

Boeing\Airbus	Maintain	Re-eng. A321XLR
Maintain	B: 62.257– A: 74.810	B:44.326—A: 92.805
Launch NMA	B: 53.792 – A: 46.488	B: 47.324 – A: 54.248

Table 13.33. Technology forcing regulations scenario payoffs

Both Airbus and Boeing will try to maintain their current products because they would achieve higher profits until they become forced to evolve due to technology regulations. It is assumed that the regulation period imposed by governments and air transport regulators will not be longer than 5 years to avoid technology stagnation.

The market share forecast does not vary from the reference scenario, but in this case, the non-recurring costs, which are related to technological development and research will increase a 20%, since when a technology regulation is implemented, manufacturers are forced to invest in R&D and to bet on re-engineering or the launch of a new aircraft.

In this equilibrium, Airbus would gain a slight advantage by obtaining more profits than Boeing, especially in the short midterm, since Airbus does not have to make a large investment in order to compete with Boeing in this scenario.

13.2.14.2 Dynamic games

In this case, it is presented a dynamic game in which it has been considered different strategies in comparison to static games. Not all possible options have been simulated, however, in this scenario, Airbus is forced to go on a new model in 10 years. The dynamic game finishes when both manufacturers decide to develop a new aircraft.

As mentioned in 13.2.13, in dynamic games, players can change strategy along the time and the game would finish when one of the manufacturers develops a new aircraft model.

In this section, the results of the different combination of strategies are presented. The strategies considered in this game are: two strategies for Boeing, "New and Delay" and three strategies for Airbus, "New, Re-engine and Delay". The objective is to find the optimal combination of strategies for both manufacturers, that is, the Nash equilibrium which is indicated in yellow colour as can be seen in the following table.

BOEING/ AIRBUS	NEW	RE-ENGINE	DELAY

NEW	B: 77-A: 61	B: 73- A: 71	B: 74- A: 76
DELAY	B: 78- A: 66	B: 79- A: 81	B: 80- A: 76

Table 13.34. Dynamic game payoffs

Using both software tools, the Nash equilibrium is computed. It can be appreciated that the results are the same for both cases. The game shows that Nash equilibrium is reached when Airbus decides to make re-engineering and Boeing decides to delay tits decision of developing a new aircraft.

The Middle of the Market is not big enough to have new aircraft models from both manufacturers because airplanes already occupy this market optimized in short and long-haul routes that are, wide-bodies and narrow-bodies aircraft.

In the case both airplanes coexist in the market, the market share would be divided equally between them, however, this situation is not sustainable.

On the one hand, Airbus decides to make re-engineering at the beginning and observe if its re-engineered model can compete with Boeing. Airbus would need 10 years to recover the investment, so they would not decide to develop a new aircraft until 2035.

On the other hand, at the beginning of the analysis period, Boeing decides to delay its decision of developing a new aircraft until 2025 because its current aircraft, the B737, has an important market share and it is a very competitive aircraft in the MoM. Boeing would not be obligated to develop a new aircraft until Airbus would launch its new models, because it would mean a significant loss of its market share.

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PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

Perspectives for Aeronautical Research in Europe

2019 Report

CHAPTER 13

Annexes

Final Report

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Annex I Aircraft specifications

AI.1 Boeing 737 MAX 8

AI.1.1 Background

The Boeing 737 is a short to medium range narrow body developed and manufactured by Boeing. It was initially introduced in 1968 and till date, it has developed into a family of thirteen passenger models with capacities from 85 to 215 passengers and it is currently Boeing's only narrow body airliner in production, with the 737 Next Generation (-700, -800, and -900ER) and the re-engined and updated 737 MAX variants in use.

The Boeing 737 Next Generation (NG) was introduced in the 1990s, with a redesigned, increased span wing, upgraded "glass" cockpit, and new interior. The 737 NG comprises the 737-600, -700, -800, and -900 variants. The 737-800 is considered commercially very successful, with more than 4000 aircraft in active service and over 24 on order backlog, the Boeing 737-800 is seen as the most liquid commercial aircraft in the market today. But the introduction of the A320neo with its efficient specifications and high sales figures put pressure on Boeing to react more quickly with a more modern and efficient 737NG successor.

Therefore, in August 2011 Boeing presented the 737 MAX aircraft type, which succeeds the Boeing 737 Next Generation (NG) and represents the fourth generation of the Boeing 737. The most important new feature of the 737 MAX was the introduction of the new CFM International LEAP-1B engine, which provides an improvement in fuel burn. In addition, fuel efficiency is improved by some aerodynamic modifications on the fuselage (a new tail cone) of the 737 MAX and the introduction of a new winglet design, called the Boeing Advanced Technology ("AT") winglet. The range of the 737 MAX has increased by 400-540nm compared to the 737NG. Aircraft types belonging to the MAX family so far are designated 737-7, 737-8, 737-8-200, 737-9 and 737-10.

As the 737-8 is considered as the successor of the 737-800 and taking into account its high sales, it is the only version of the 737 MAX family analysed in the study. The 737-8 is a narrow-body short to medium range airliner. It can carry between 178 and 210 passengers and it has a range up to 3550nm. The first flight took place in 2016. The 737-8 competes against its arch-rival the A320neo. So far, 2,556 orders have been placed for the 737-8 variant, making it the most popular 737 MAX variant.

As there are still a large number of 737-800 in operation, it is expected that the 737 MAX 8 will replace a high part of this fleet, especially considering its order book, which is very promising. Therefore, it will be a competitor to consider the new NMA aircraft.

AI.1.2 Technical specifications and performance metrics

AI.1.2.1 B737 MAX 8

DIMENSIONS

Overall length (m)	39.52 m
Wingspan (m)	35.9 m
Height (m)	12.3 m

CAPACITY

Typical seating	178 (two-class)
Max	210

ENGINE DATA

SL thrust (ton)	12.23
Weight (Kg)	2780
Number of engines	2

PERFORMANCE

Range (nm)	3550
Maximum take-off weight (Kg)	82191
Operating empty weight (Kg)	45070

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	842
Utilization (block hours per day)	11
Fuel consumption (Gallons per block hour)	700

AI.1.3 Order book

The B737 MAX 8 is a very successful program which has accumulated a great number of orders, as in the case of the A321neo which is its main rival. By December 2018, the MAX 8 had received 2590 orders, composed of 330 deliveries and a backlog of 2260 (Figure 1). Considering that it is expected the 737 MAX 8 will replace a part of the 737-800 fleet, its future perspectives are very optimistic, although the A321neo is absorbing part of its market share.

Orders	Deliveries	Backlog
2590	330	2260

Data as of December-2018

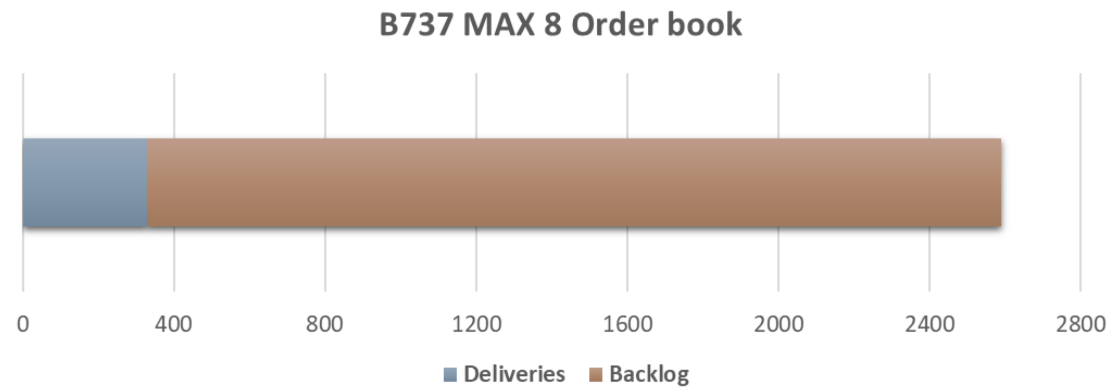


Figure 1. B737 MAX 8 Order book

AI.1.4 Routes analysis

The market share of the routes shown in Figure 2 belongs to the B737-800 variant since the B737 MAX 8 has just entered the market and there are few routes flown by this model. In addition, as the MAX 8 is expected to be the successor of the B737-800 variant it is very likely that the routes of both models will be very similar when there are more units of the MAX 8 in the market.

The figure shows a distribution very similar to the A321neo variant, its main rival. That is, more than 70% of the routes flown by this model are less than 1000 nm in length. The rest is distributed in the range between 1000 and 3000 nm, in such a way that as the distance increases, the number of routes is reduced, and as of a length of 3000nm, there are no routes flown by the B737-800.

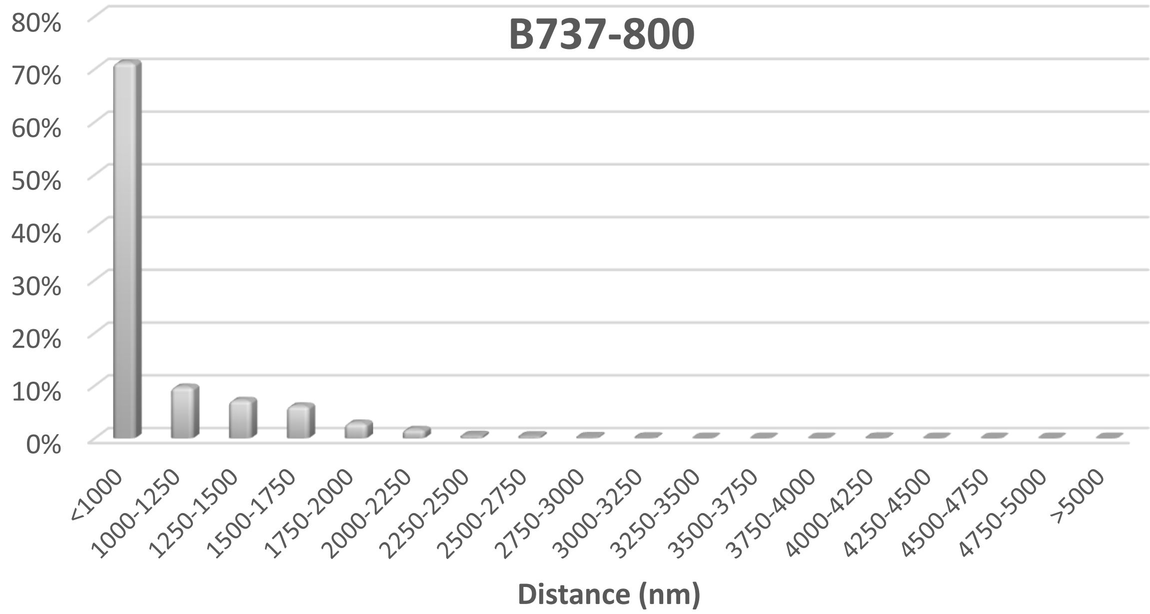


Figure 2. B737 MAX 8 routes market share

AI.2 Airbus 330/330neo

AI.2.1 Background

The Airbus A330 is a medium to long-range wide-body twin-engine jet airliner made by Airbus. It entered service in 1994 and it was offered in two versions: the shorter A330-200, which is capable of flying up to 6540nm with about 240 passengers, and the longer A330-300 variant, which has a range of up to 5400nm with 300 passengers.

Initially, Airbus positioned the A330-200 as an efficient, more capable and more comfortable alternative to the Boeing 767-300ER. It had initial sales success, due to its newer technology, superior range capability and crew commonality with the A320 and A340 families, making it the preferred choice in its category. However, since 2013, the A330-200 was finally outsold by the A330-300, as it is a more efficient aircraft, with almost the same range to offer as the A330-200 with far more passenger load. The A330-200 backlog is currently around 31 aircraft.

On the other hand, the A330-300 was optimized for medium-range high-density markets and with a backlog of around 23 aircraft, it is still popular, especially for Asian operators. In addition, it is still an efficient competitor in medium and long haul routes ahead other heavier aircraft such as the A350 variants, which have much higher capital cost and are optimized for longer range operations.

Airbus launched a new version of the A330, the A330neo, using the same principles employed to develop the A320neo and benefiting from engine technology developed for the A350 XWB. The engine option for the A330neo will be the new RR Trent 7000 engines. These engines together with other improvements such as new larger winglets, an increased wingspan and an optimized cabin will result in 11% lower trip costs and (thanks to 10 extra seats) 14% lower fuel burn per seat. Besides, the A330neo has a 95% parts commonality with the previous generation A330s and both generations have the same type of rating. This minimizes the entry in service costs for airlines that already operated the A330, as they would not need to invest significant amounts on new spares or additional flight crew training.

The A330neo comes in two sizes, the A330-800N and A330-900N. On the one hand, the A330-800N is the smaller of the two and it will be the successor of the A330-200. As of December 2018, the order book for the A330-800N is extremely small with only 8 aircraft ordered and, due to the little interest shown by airlines, it seems very unlikely that Airbus will spend any money on the further development of this aircraft. On the other hand, the A330-900N will be the successor of the A330-300 and with a backlog of 227, the A330-900N is far more popular than the A330-800N, so the main focus of the A330neoprogramme will be on the -900N variant. The A330-900N is capable of transporting 287 passengers in a two-class cabin layout over a distance of 6500nm.

The market analysis of the following sections has not been made for the A330-800N due to its little success, as the future perspectives are not optimistic.

AI.2.2 Technical specifications and performance metrics

AI.2.2.1 A330-200

DIMENSIONS

Overall length (m)	58.82
Wingspan (m)	60.30
Height (m)	17.39

CAPACITY

Typical seating	247 (two-class)
Max	406

ENGINE DATA

SL thrust (ton)	26.2
Weight (Kg)	5850
Number of engines	2

PERFORMANCE

Range (nm)	7250
Maximum take-off weight (Kg)	242000
Operating empty weight (Kg)	120000

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	871
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	1750

AI.2.2.2 A330-300

DIMENSIONS

Overall length (m)	63.66
Wingspan (m)	60.30
Height (m)	16.79

CAPACITY

Typical seating	277 (two-class)
Max	440

ENGINE DATA

SL thrust (ton)	29.57
Weight (Kg)	5850
Number of engines	2

PERFORMANCE

Range (nm)	6350
Maximum take-off weight (Kg)	242000
Operating empty weight (Kg)	129400

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	871
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	1900

AI.2.2.3 A330-900N

DIMENSIONS

Overall length (m)	63.66
Wing span (m)	64
Height (m)	16.79

CAPACITY

Typical seating	277 (two-class)
Max	440

ENGINE DATA

SL thrust (ton)	30.0
Weight (Kg)	6200
Number of engines	2

PERFORMANCE

Range (nm)	7200
Maximum take-off weight (Kg)	251000
Operating empty weight (Kg)	132000

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	918
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	1450

AI.2.3 Order book

As illustrated in Figure 3, historical orders of the A330 show that it has been a successful program for a widebody type, especially for the A330-300 version which has accumulated a total of 789 orders as of December 2018, although the A330-200 follows it closely with 665 orders to date. Besides, the A330-900N version, which was developed as the successor of the A330-300, is quite popular achieving a great number of orders the first years. However, because it is a new version, there have only been three deliveries, resulting in a backlog of 231 aircraft (Figure 5). In terms of deliveries, both A330 old versions have maintained a high production rate in the last years.

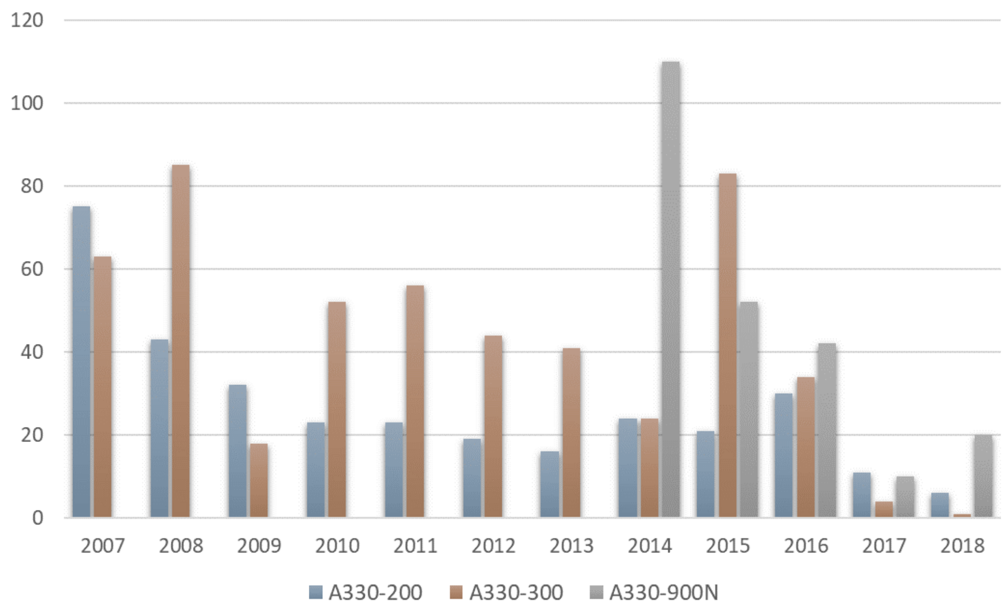


Figure 3. A330/A330neo annual orders

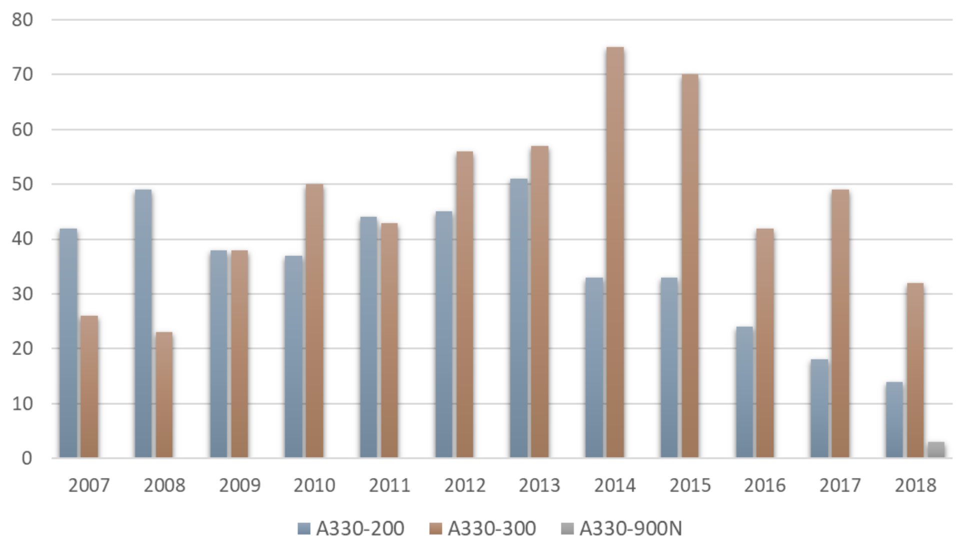


Figure 4- A330/A330neo annual deliveries

	Orders	Deliveries	Backlog
A330-200	665	633	32
A330-300	789	765	24
A330-900N	234	3	231

Data as of December-2018

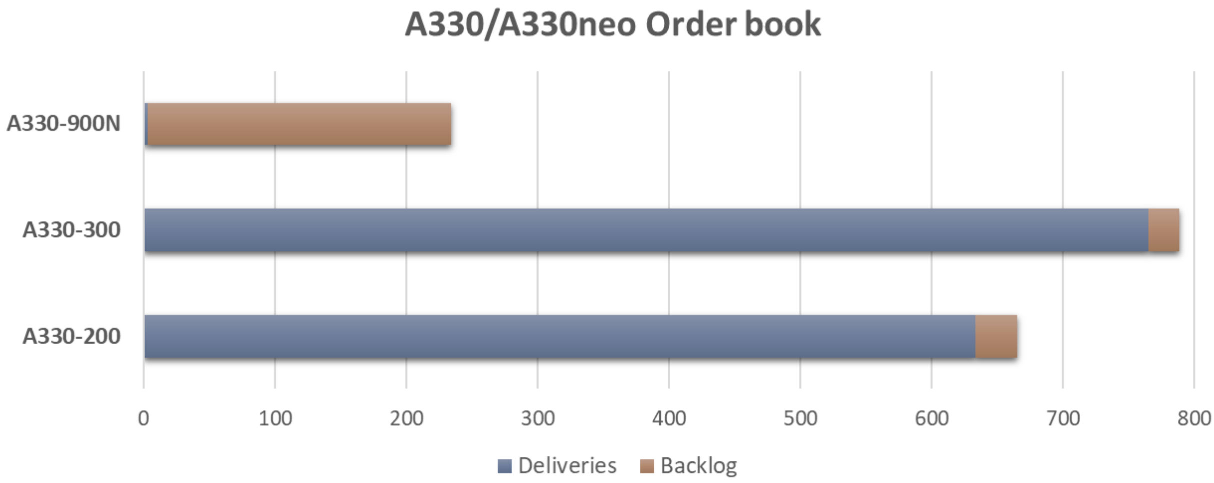


Figure 5. A330/A330neo order book

AI.2.4 Routes analysis

The routes market share are shown in Figure 6 and Figure 7 for the A330-200 and A330-300 variants, indicating that distances flown by these models are more or less equally distributed by sections, which is a typical situation for this type of aircraft due to their larger range. However, it is important the fact that the higher percentage of routes flown by these models is found in the category of less than 1000 nm, especially considering that their range varies from 6350 to 7250 nm, depending on variant.

It is particularly remarkable the case of the A330-300 variant, where routes of more than 5000nm only represent the 1%, while routes of less than 1000nm represent 22%, the highest percentage.

On the other hand, as the A330-900N has just entered the market, there are few routes flown by this model. This variant is expected to be the successor of the A330-300 model; therefore, it is very likely that the routes of both models will be similar when there are more units in the market.

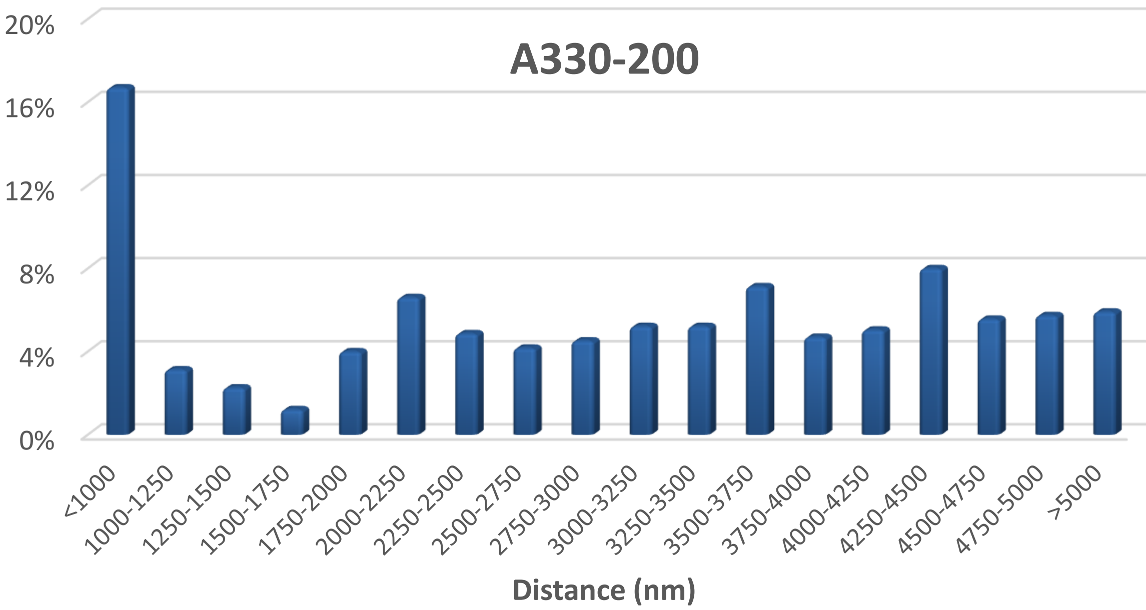


Figure 6. A330-200 routes market share

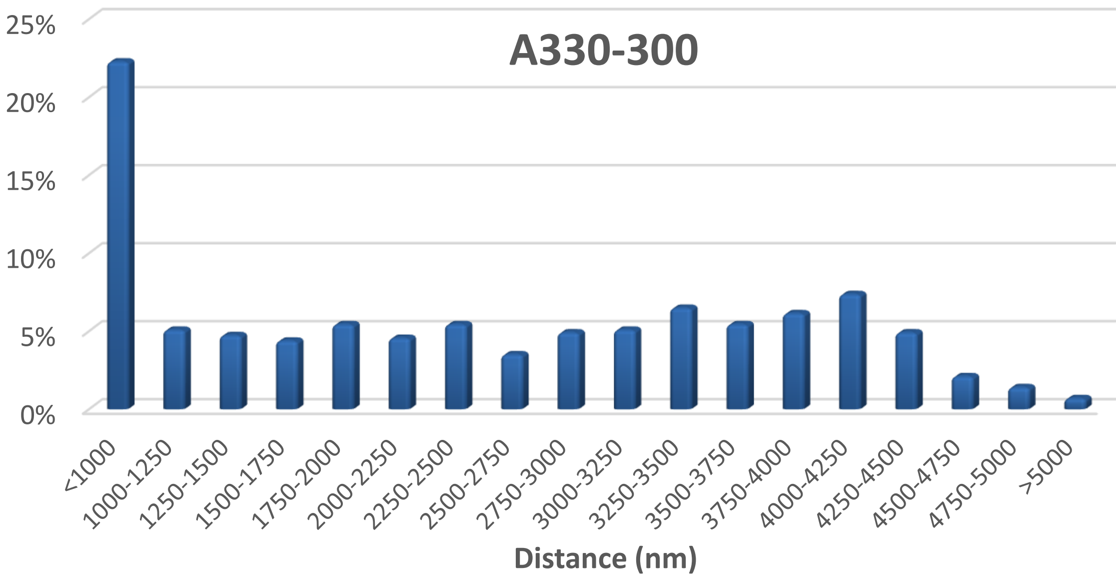


Figure 7. A330-300 routes market share

AI.3 Boeing 787

AI.3.1 Background

The Boeing 787 Dreamliner is a long-haul, mid-size widebody, twin-engine jet airliner manufactured by Boeing. It entered service in 2011 and it has been offered in three versions: the shortest 787-8, the longer 787-9 and the 787-10 as the longest variant. In this study, it is analysed the 787-8, which is the base model of the 787 family with a typical capacity of 242 passengers and a range of 7355 nm.

The 787 family was initially designed to replace the 757- and 767-products, and it is the most successful wide-bodied aircraft design ever in terms of aircraft ordered prior to its entry into service. The 787 family features many new technologies like a full composite structure including wing and barrel-shaped fuselage sections, new up to 15-20% more efficient and relatively quiet engines, improved aerodynamics and many new electric systems instead of pneumatics/hydraulics.

The 787-8 is the 'baseline model' and it is optimized for the long-range medium-density markets and it would serve as a potential replacement for the 767-300ER. Besides, its ultra-long-range capability enables it as well to develop new point-to-point routes, allowing airlines to develop routes between city-pairs at long range that have insufficient traffic density to justify the larger long-range aircraft types.

After its initial success, the 787-8 program had several problems due to various reasons (delays, failures of battery systems, some incidents), resulting in a reduction in terms of orders. In fact, a significant number of 787-8 orders have been swapped to the 787-9 variant. The 787-9 is closer to the 777-200ER in terms of payload-range and compared to the baseline 787-9, it has more powerful engines and a stretched fuselage which enables it to carry up to 290 passengers over an additional range. Although the 787-9 exceed in range and capacity those values estimated for the Middle of the Market, the routes analysis performed in section 13.2.4 indicates that it is a model used for these types of routes. Therefore, it has been decided to include its analysis. On the other hand, the 787-10 variant is hardly used for the MoM routes.

AI.3.2 Technical specifications and performance metrics

AI.3.2.1 Boeing 787-8

DIMENSIONS

Overall length (m)	57
Wingspan (m)	60
Height (m)	16.92

CAPACITY

Typical seating	248 (two-class)
Max	359

ENGINE DATA

SL thrust (ton)	28.10
Weight (Kg)	5900
Number of engines	2

PERFORMANCE

Range (nm)	7305
Maximum take-off weight (Kg)	227950
Operating empty weight (Kg)	117480

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	903
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	1628

AI.3.2.2 Boeing 787-9

DIMENSIONS

Overall length (m)	63
Wingspan (m)	60
Height (m)	17.02

CAPACITY

Typical seating	296 (two-class)
Max	406

ENGINE DATA

SL thrust (ton)	30.0
Weight (Kg)	6000
Number of engines	2

PERFORMANCE

Range (nm)	7530
Maximum take-off weight (Kg)	254000
Operating empty weight (Kg)	135500

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	903
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	1700

AI.3.3 Order book

The 787-8 had really an initial success, accumulating a significant number of orders. However, several problems related to delays and incidents caused that a significant number of 787-8 orders were swapped to the 787-9 variant and since 2010 there have been very few new orders for this variant. On the other hand, the 787-9 is the preferred variant, achieving a total of 810 orders and with a backlog of 404 (Figure 9). As of December 2018, it has clearly outsold the 787-8. Besides, the production rate of the 787-9 has been increasing since its introduction in 2014, reaching a peak of 120 units in 2018 (Figure 8).

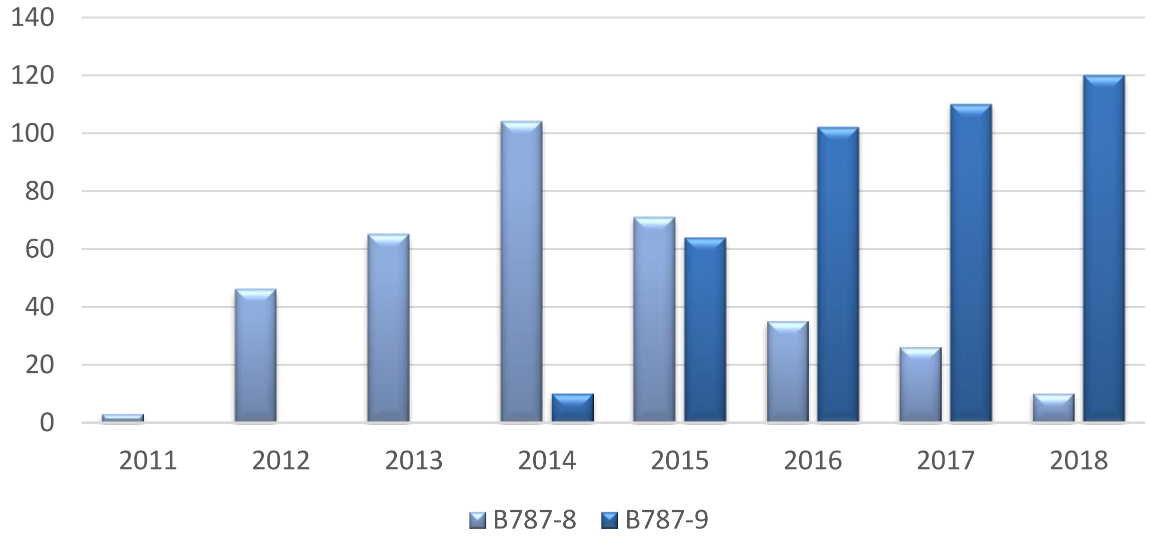


Figure 8. B787 annual deliveries

	Deliveries	Backlog
B787-8	360	84
B787-9	406	404

Data as of December-2018

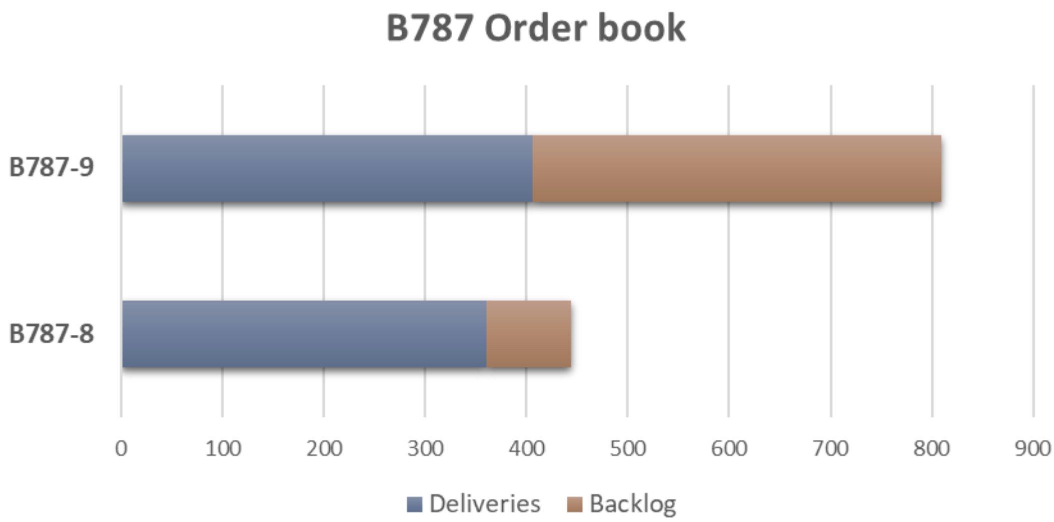


Figure 9. B787 order book

AI.3.4 Routes analysis

As in the case of the A330, distances flown by these models are more or less equally distributed by sections, which is a typical situation for this type of aircraft due to their larger range. However, in this case, the highest percentage of routes flown is found in the category of more than 5000 nm, which is a reasonable result taking into account that their range varies from 7355 to 7635 nm, depending on variant.

On the one hand, most of the 787-8 routes are concentrated in the rank between 3000 and 5000nm, with almost 50% of the routes. The routes with more than 5000nm of distance represent 17%, which is the highest percentage. On the other hand, most of the 787-9 routes are also concentrated in the rank between 3000 and 5000nm, with almost 48% of the routes. However, routes with more than 5000nm of distance represent a significant percentage, 31%. This fact is normal as the 787-9 has a larger range than the 787-8.

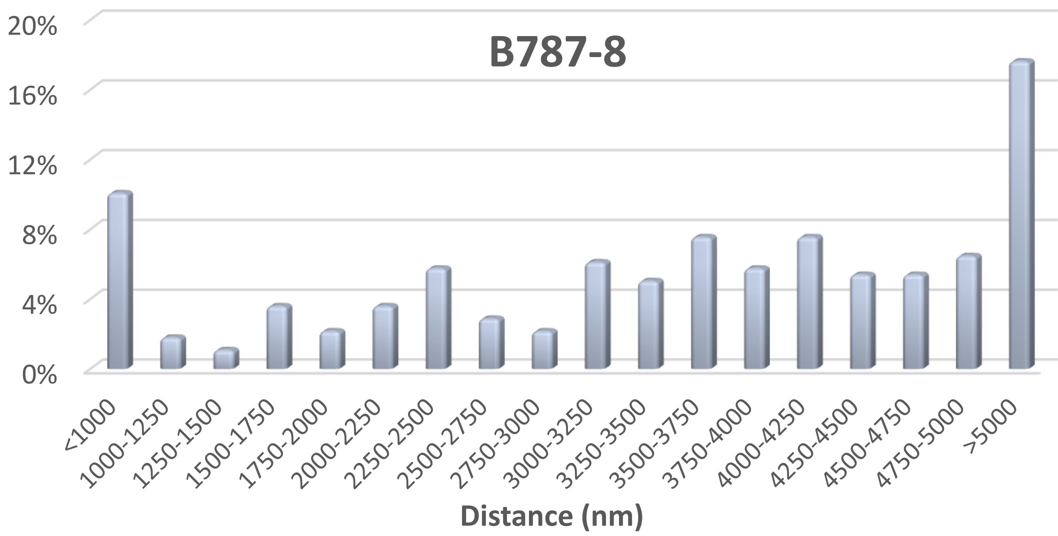


Figure 10. B787-8 routes market share

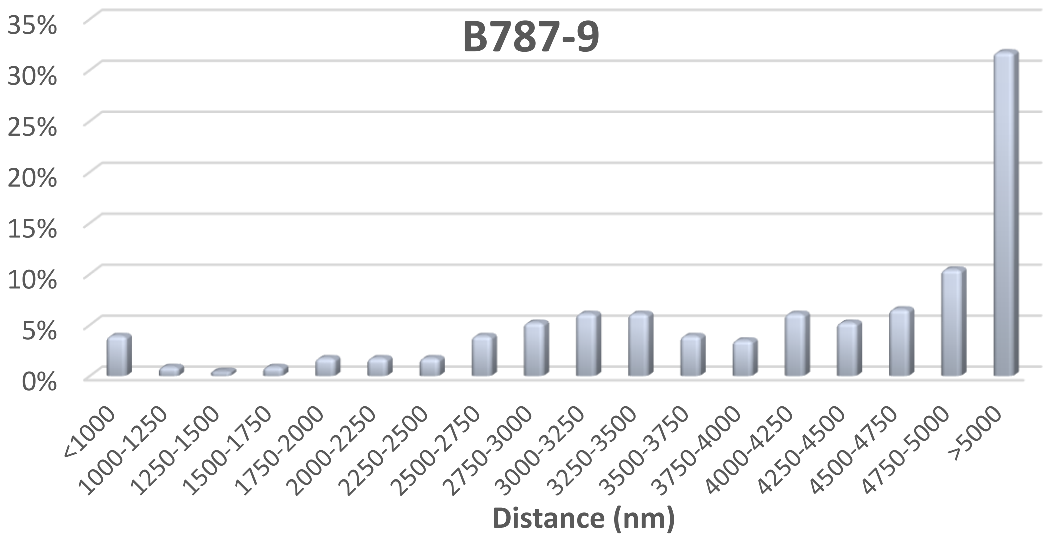


Figure 11. B787-9 routes market share

AI.4 Boeing 757

AI.4.1 Background

The Boeing 757 is a mid-size, narrow-body twin-engine jet airliner that was manufactured by Boeing. It entered service in 1983 and it was offered in two versions: the shorter 757-200 and the stretched 757-300, which can carry 200 to 295 passengers for a maximum of 3150 to 4100 nm depending on variant.

On the one hand, the 757-200, the original version of the aircraft, entered service in 1983. It was developed in conjunction with the wide-bodied 767 program. As a result, the 757-200 shares some components with the 767 and has a common crew rating. The 757 was designed for trans-continental markets that had outgrown the then-available 727.

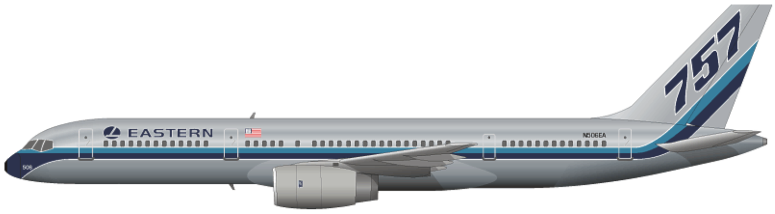
On the other hand, the 757-300 was a last-minute and essentially unsuccessful attempt to revitalize the 757 market by introducing a stretched version. After offering only one version for almost two decades, this longer version (40 more passengers in dual class) was offered as well. However, by the end of the 1990s, the 20-year-old technology of the 757 was considered outdated and the trend in the narrow-bodied aircraft market was towards smaller aircraft used with high frequency instead of larger. As a result, the 757-300 never had any success commercially and production was ended only five years after it first entered into service. There are only 55 of these aircraft in service and United, Delta and Condor are the most important operators.

In its first years of production, the 757 attracted many orders from major carriers and charter airlines alike. Nevertheless, for the higher frequency mainline operations, legacy carriers and more importantly low-cost airlines, mostly selected A320 family or 737NG aircraft, when these aircraft became available on the market. The 757's transcontinental range made the aircraft heavy in comparison to the more modern A320 family and 737NG.

Boeing decided to end the 757 production in 2004. Although the part out phase had already started for older 757s, large fleets of younger 757s remained in passenger service, particularly at some US majors. Nowadays, 323 of these aircraft remain in service. The purpose of Boeing is introducing a New Midsize Aircraft (NMA) to replace the 757 model together with the 767. For this reason, these models are analysed in this section to study their main routes and fleet state.

AI.4.2 Technical specifications and performance metrics

AI.4.2.1 Boeing 757-200



DIMENSIONS

Overall length (m)	47.3
Wingspan (m)	38
Height (m)	13.6

PERFORMANCE

Range (nm)	3915
Maximum take-off weight (Kg)	115660
Operating empty weight (Kg)	58400

CAPACITY

Typical seating	200 (two-class)
Max	239

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	868
Utilization (block hours per day)	10.5
Fuel consumption (Gallons per block hour)	1300

ENGINE DATA

SL thrust (ton)	18.05
Weight (Kg)	3700
Number of engines	2

AI.4.3 Total orders

Production of the 757 ended in October 2004. Over the duration of the program, 1049 757s were delivered from 54 customers. The 757-200 was by far the most popular model, with 913 units built. The last 757 was delivered to Shanghai Airlines in November 2005. In December 2018, a total of 378 of these models were still in operation.

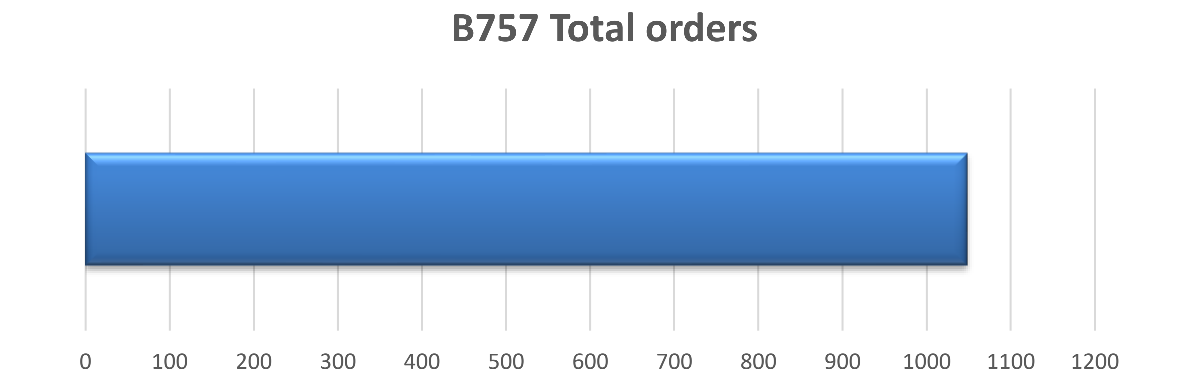


Figure 12. B757 Total orders

AI.4.4 Routes analysis

Most of the 757 routes are concentrated in the rank between 1000 and 3000nm as well as in the category of less than 1000 nm. As of a length of 3000nm, these models are hardly used. This routes distribution is quite similar to the single-aisle segment, where routes are concentrated below 3000nm. For this reason, it is very likely that part of this fleet will be replaced by models such as the A321LR or B737 MAX 8.

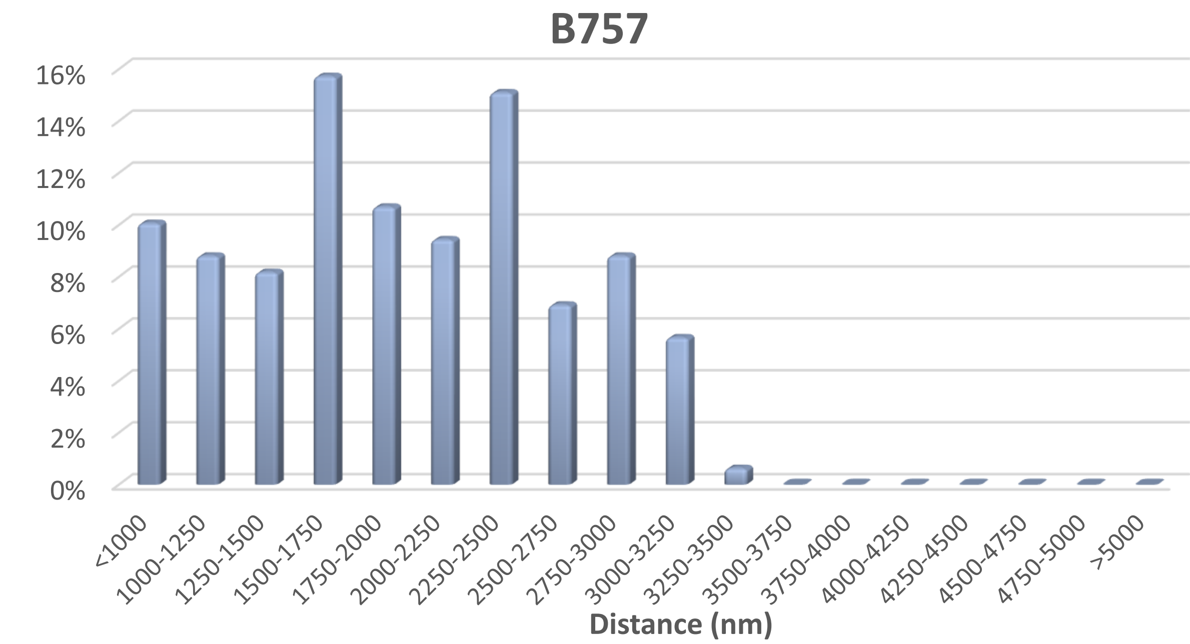


Figure 13. B757 routes market share

AI.5 Boeing 767

1.1.1 Background

The Boeing 767 is a mid-to large-size, medium to long-range, widebody twin-engine jet airliner manufactured by Boeing. Designed as a smaller wide-body airliner than earlier aircraft such as the 747, the 767 has a seating capacity for 181 to 375 passengers, and a design range of 3,850 to 6,385 nm, depending on variant. The original 767-200 entered service in 1982, followed by the 767-300 in 1986 and the 767-400ER, an extended-range (ER) variant, in 2000.

The 767-200 is the smallest of the three variants and is offered in a basic and a high gross weight (-200ER extended range) version. Many passenger 767-200/200ER aircraft have already been dismantled and a high percentage of the current fleet is stored, being only 13 in service at present.

The basic 767-300 is essentially a 45 seat stretch of the 767-200, and it is mostly used in the North American and transatlantic market as well as the Asian domestic (Japan) and regional markets. Boeing almost simultaneously developed the higher gross weight 767-300ER which has up to 2,000 nm of additional range, a standard lower deck large cargo door and is mostly used on intercontinental routes. The 767-300ER is the most successful member of the 767 family, selling over 500. However, like the 757, the 767 is technically outdated, a problem that became obvious after the introduction of the A330-200 which is more efficient and more capable. Many airlines, therefore, replaced their 767-300ERs with the new Airbus products.

In 2014, the last passenger 767-300ER was delivered. The A330-200 still records moderate sales and has already outsold the 767-300ER. Currently, US majors still operate the majority of the 767-300(ER) fleet, with 381 aircraft in service. Boeing's 787 will replace a large part of all 767s in the near future unless Boeing develops the new mid-size aircraft as a replacement.

Like the 757-300, the 767-400ER was a failed attempt by Boeing to revive a 20-year-old program. It was launched to create a better competitor to the successful A330-200. The 767-400ER is a 40 seat stretch of the already-stretched 767-300 fuselage. Market acceptance of the 767-400ER was awful, with only two airlines buying the aircraft as it largely featured 20-year-old technology. Today Delta Airlines (with 21 aircraft) and United Airlines (with 16 aircraft) operate the 767400ER.

Currently, the firm orders correspond to the 767-300 freighter version. In July 2015, FedEx placed a firm order for 50 Boeing 767 freighters with deliveries from 2018 to 2023.

With the introduction of its new mid-size aircraft, the 797, Boeing aims to replace the 767 fleet as its initial design shows a similar range and capacity capabilities between both models. For this reason, the 767 variants are analysed in this section to study their main routes and fleet state.

AI.5.1 Technical specifications and performance metrics

AI.5.1.1 Boeing 767-300ER

DIMENSIONS

Overall length (m)	54.94
Wingspan (m)	47,57
Height (m)	16.80

PERFORMANCE

Range (nm)	5980
Maximum take-off weight (Kg)	186900
Operating empty weight(Kg)	90010

CAPACITY

Typical seating	261 (two-class)
Max	351

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	850
Utilization (block hours per day)	11
Fuel consumption (Gallons per block hour)	1554

ENGINE DATA

SL thrust (ton)	26.2
Weight (Kg)	4100
Number of engines	2

AI.5.2 Order book

The 767 was the first twinjet widebody type to reach 1000 aircraft delivered. As of December 2018, Boeing has received 1248 orders for the 767 from 74 customers with 1139 delivered. The most popular variant is the 767-300ER with 583 delivered. Non-passenger variants of the 767 remain in production so that the orders unfilled belong to the 767 freighter. Currently, more than 700 of these aircraft are in service.

Orders	Deliveries	Backlog
1248	1139	109

Data as of December-2018

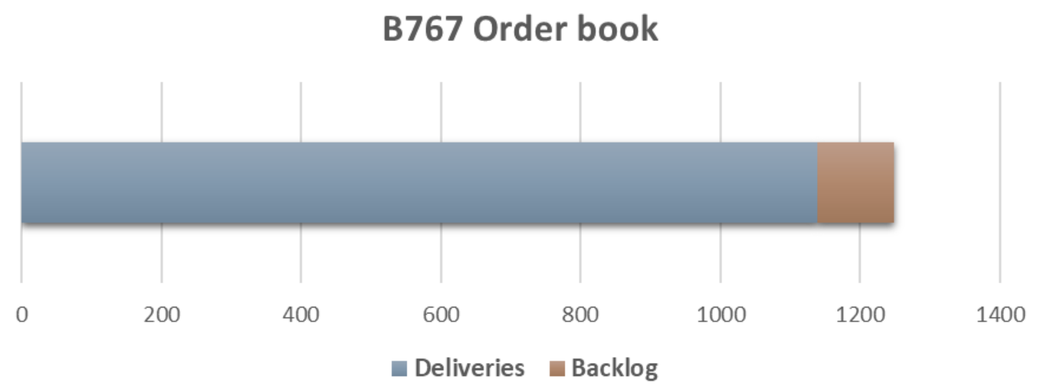


Figure 14. B767 Order book

AI.5.3 Routes analysis

As opposed to the B757 case, distances flown by B767 models are more or less equally distributed by segments, which is reasonable as they possess more range. The highest market share is concentrated in the range between 3000 to 5000nm, with a 51% percentage, which indicates their great importance for the MoM segment. The main objective of the new Boeing NMA will be absorbed routes belonging to these models.

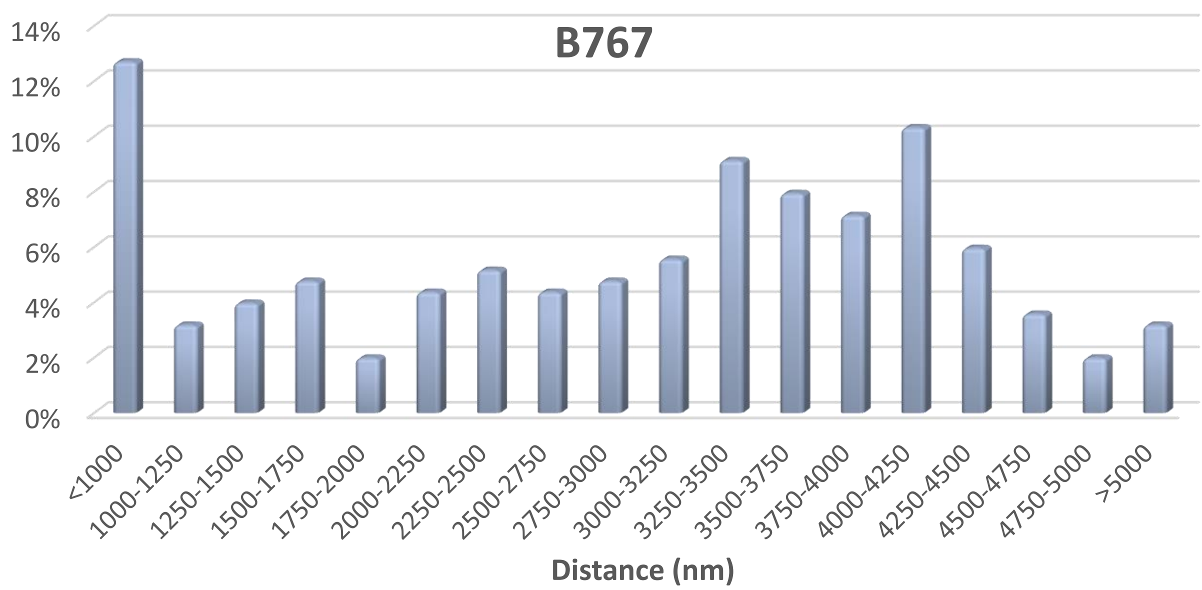


Figure 15. B767 routes market share

AI.6 Boeing 777

AI.6.1 Background

The Boeing 777 is a long-range wide-body twin-engine jet airliner developed and manufactured by Boeing. It has a typical seating capacity of 314 to 396 passengers, with a range of 5240 to 8555 nm, depending on variant. The original 777-200 variant entered commercial service in 1995, followed by the extended-range 777-200ER in 1997 and the stretched 777-300 f in 1998. The extended-range 777-300ER and ultra-long-range 777-200LR variants entered service in 2004 and 2006 respectively.

The Boeing 777-family was developed to fill the capacity gap between the 767 and 747-400 and to replace older wide bodies as DC-10-10 and L-1011 Tristar. Compared to previous aircraft generations, the 777's largely computerized assisted design featured improved, more reliable engines, a higher percentage of composites in the structure, digital fly-by-wire and a modern LCD cockpit.

On the one hand, the 777-200 aimed at the US high-density, transcontinental and intra-Asia market. However, the strong competition from the low-cost carriers as well as the more efficient A330 limited the commercial success of the 777-200. In total, the model has received a total of 88 orders and today still eight airlines operate the type. The extended-range 777-200ER was optimized on markets such as Europe to the US West Coast and offered some 2500 nm range over the 777-200. Its payload/range performance combined with the efficiency of twin-engines made the 777-200ER the fastest-selling wide-bodied until the 787 was launched. In total, 777-200ER has received a total of 422 orders and most of them are still in service. Finally, the 777-200LR is an ultra-long-range derivative of the 777-200ER which was designed to counter the A340, with little success.

On the other hand, the 777-300 was designed to operate on the mid-to-long range high-density routes but it hardly succeeded with only 60 orders in total. Currently, it is almost exclusively used within Asia by the large network carriers. On the other hand, its extended-range variant, the 777-300ER, has become one of the most successful Boeing wide-bodied aircraft in history, with around 800 aircraft built and delivered and a backlog of 43 aircraft. Initially, the 777-300ER sales were slow but the longer- term 747 replacement market and the limited competition from Airbus' much less efficient four-engined A340-600 almost gave the 777-300ER a monopoly in its market segment.

In 2013, Boeing announced the 777X program, which is a revamp of the current 777 generation including new engines, redesigned wings other modifications and it is scheduled to enter service around 2020.

AI.6.2 Technical specifications and performance metrics

AI.6.2.1 Boeing 777-200/200ER

DIMENSIONS

Overall length (m)	63.73
Wingspan (m)	60.93
Height (m)	18.5

CAPACITY

Typical seating	313 (two-class)
Max	440

ENGINE DATA

SL thrust (ton)	38
Weight (Kg)	7893
Number of engines	2

PERFORMANCE

Range (nm)	7065
Maximum take-off weight (Kg)	247200
Operating empty weight(Kg)	138100

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	892
Utilization (block hours per day)	12
Fuel consumption (Gallons per block hour)	2289

AI.6.2.2 Boeing 777-300/300ER

DIMENSIONS

Overall length (m)	73.86
Wingspan (m)	64.80
Height (m)	18.5

PERFORMANCE

Range (nm)	7370
Maximum take-off weight (Kg)	351533
Operating empty weight (Kg)	167829

CAPACITY

Typical seating	396 (two-class)
Max	550

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	892
Utilization (block hours per day)	12
Fuel consumption (Gallons per block hour)	2659

ENGINE DATA

SL thrust (ton)	45.0
Weight (Kg)	8762
Number of engines	2

AI.6.2.3 Boeing 777-X

DIMENSIONS

Overall length (m)	69.80
Wingspan (m)	71.80
Height (m)	19.5

CAPACITY

Typical seating	365 (two-class)
Max	-

ENGINE DATA

SL thrust (ton)	47
Weight (Kg)	8762
Number of engines	2

PERFORMANCE

Range (nm)	8690
Maximum take-off weight (Kg)	351500
Operating empty weight (Kg)	181000

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	892
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	2260

AI.6.3 Order book

The 777 first entered commercial service in 1995. Since then, it has received more orders than any other wide-body airliner. As of December 2018, more than 60 customers had placed 1412 orders for these variants, with 1369 delivered. The most successful variant is the 777-300ER, with 799 delivered and 842 orders. On the other hand, the B777X, of which introduction is expected around 2020, has received 344 so far.

	Orders	Deliveries	Backlog
B777-200	88	88	0
B777-200ER	422	422	0
B777-300	60	60	0
B777-300ER	842	799	43
B777-X	344	0	344

Data as of December-2018

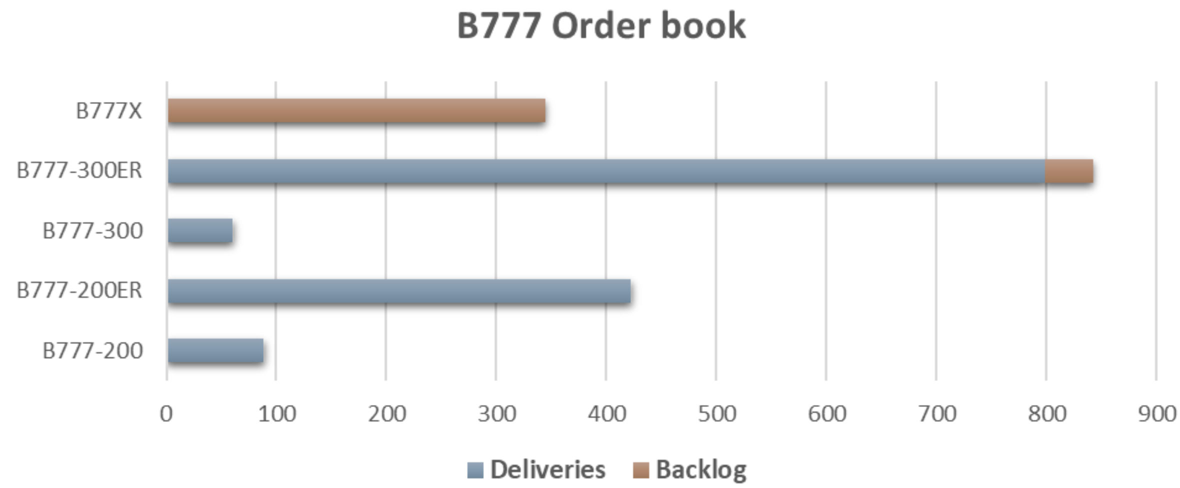


Figure 16. B777 Order book

AI.6.4 Routes analysis

B777-200 and B777-300 versions are aircraft with more than 6000 nm of range so that most of the market share is concentrated in routes which surpass 5000nm., especially in the case of B777-200ER/300ER variants, which are designed for longer routes. However, some of these aircraft also have a significant market share within the MoM segment like the B777-200. For this reason, it is required to consider these models for the market analysis as well as their improved version, the B777X, which is expected to replace these aircraft in the near future.

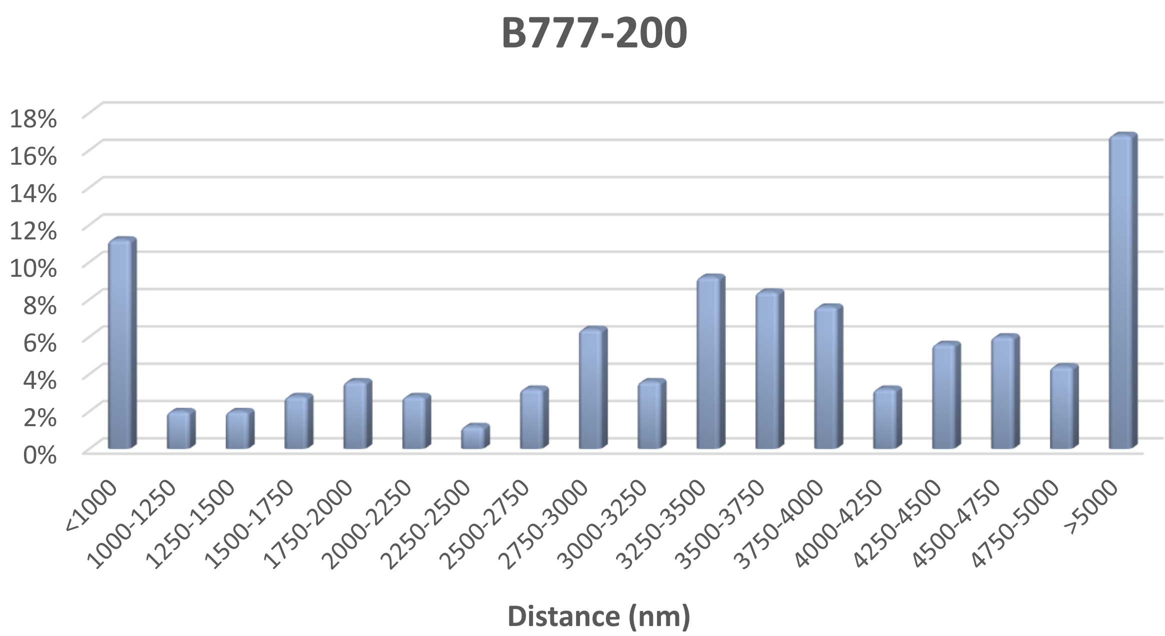


Figure 17. B777-200 routes market share

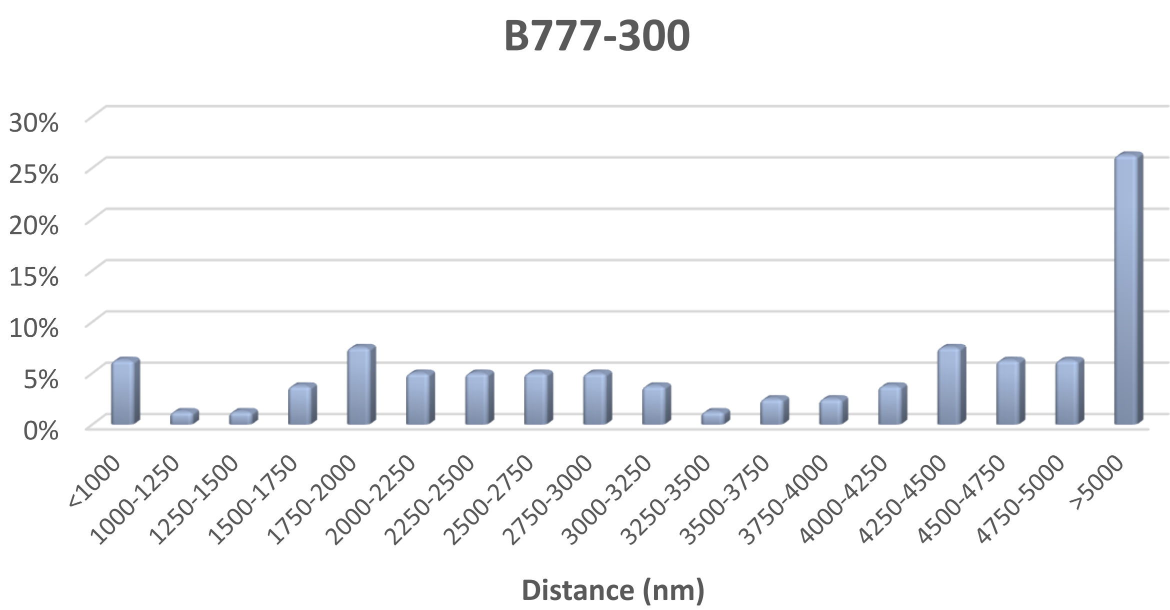


Figure 18. B777-300 routes market share

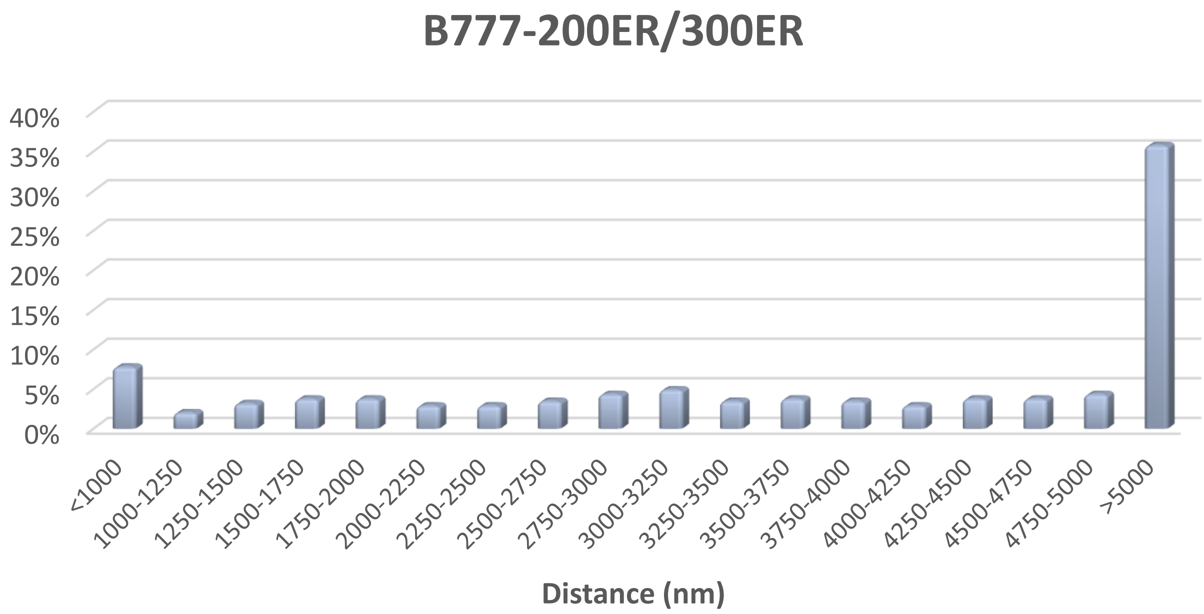


Figure 19. B777-200ER/300ER routes market share

AI.7 Airbus A350

AI.7.1 Background

The Airbus A350 XWB is a family of long-range, twin-engine wide-body jet airliners developed by Airbus. The A350 is the first Airbus aircraft with both fuselage and wing structures made primarily of carbon fibre reinforced polymer. Its variants seat 315 to 369 passengers in typical seating layouts with a range of 8100 to 8700 nm. The A350 is positioned to compete with the B787 and B777 families. It is also considered to be the future twin-engine replacement of the A330/A340 family as well.

Initially, its first launch was in 2004 with the A350-800 variant but it failed as it was considered only an upgraded A330 which would not be able to compete with the B787. Airbus responded with the redesigned A350 'XWB' (eXtra Wide Body) which featured a wider fuselage, a new (composite) wing, upgraded A380 based systems and an advanced technology cockpit. The A350-900 was the first and baseline A350 model and entered service with Qatar Airways in January 2015. In terms of payload-range, the A350-900 is positioned closest to the 777-200ER which has 400nm less range and slightly lower seat capacity. The slightly smaller 787-9 and stretched 787-10 are competitors as well.

Currently, with 257 aircraft in service and around 450 A350-900s on order, it is by far the most popular variant of the A350 family. The A350-1000 is a stretched version of the A350-900 which can accommodate 40 more seats. This largest member of the A350 XWB family entered service in 2018. In terms of payload-range, the A350-1000 is expected to be a competitor to the 777-300ER which has the same range and thirty more seats. So far, 180 A350-1000s have been ordered, indicating that this model is not as popular as the A350-900.

In the analysis, it is only included the A350-900 was it is the most successful program and, in addition, the A350-1000 does not possess market share for the MoM segment.

AI.7.2 Technical specifications and performance metrics

DIMENSIONS

Overall length (m)	66.,80
Wingspan (m)	64.75
Height (m)	17.05

PERFORMANCE

Range (nm)	8100
Maximum take-off weight (m)	279866
Operating empty weight (m)	142400

CAPACITY

Typical seating	315 (two-class)
Max	440

COST MODEL INPUT PARAMETERS

Speed (Kilometres per hour)	903
Utilization (block hours per day)	12.5
Fuel consumption (Gallons per block hour)	1950

ENGINE DATA

SL thrust (ton)	40.0
Weight (Kg)	7277
Number of engines	2

AI.7.3 Order book

Figure 20 shows the order book of the A350-900 in terms of deliveries and backlog. The A350-900 is the most successful variant, with more than 714 orders and a backlog of 456 aircraft.

	Orders	Deliveries	Backlog
A350-900	713	257	456

Data as of December-2018

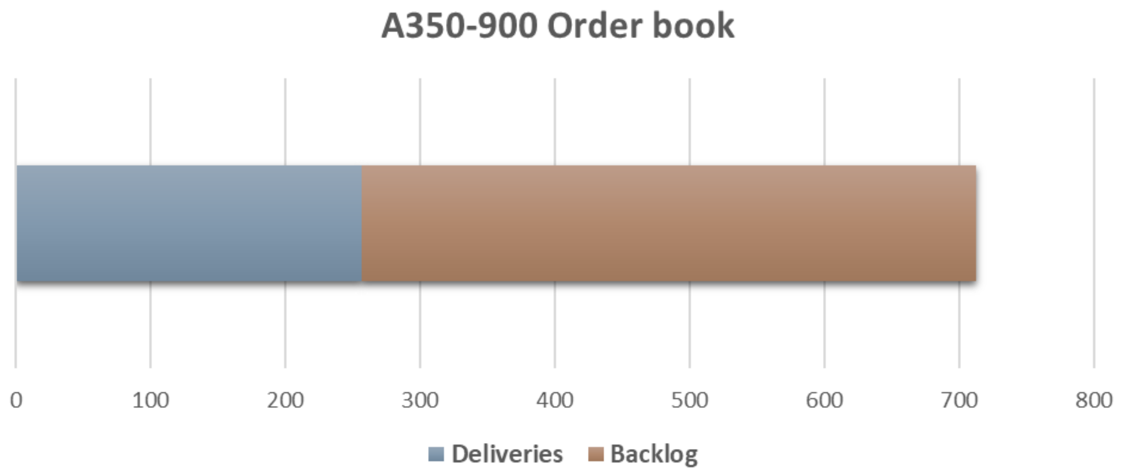


Figure 20. A350-900 order book

AI.7.4 Routes analysis

Although the A350 is a model designed for longer routes, it is also used for MoM routes, but with a small proportion. Due to its recent introduction in the market, it is very likely that this percentage will change in the future, considering order book perspectives.

Only the A350-900 variant has a market share for this type of routes while the A350-100 is used for routes which surpass 5000 nm. For this reason, the A350-100 has been excluded from the analysis.

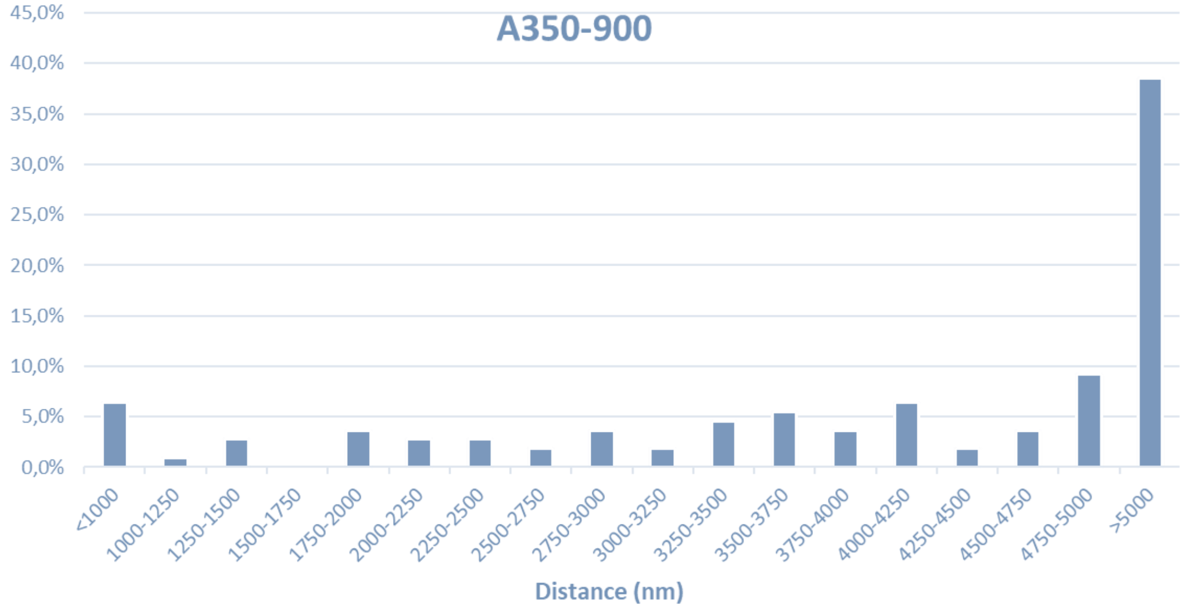


Figure 21. A350-900 routes market share

Annex II Roadmap for engines fuel efficiency.

In this section, we perform a detailed analysis of current and future technology to improve engines fuel efficiency, as well as its expected date of entry into service. A comparative analysis of the different engines considering its advantages and inconveniences is also included.

AII.1 The way to improve engine fuel efficiency

The main objectives of advanced research and development of aircraft gas turbine engines (GTE) are to improve their fuel efficiency, reduce the weight and cost of the life cycle, increase reliability and durability while simplifying maintenance, and lower emissions of harmful substances and noise. As it is shown in [1] for the period under review, the fuel efficiency of the aircraft was raised: by reducing the specific engine consumption by 69% of the overall improvement in the fuel efficiency; due to aerodynamic improvements of the airframe by 27%; due to other factors about 4%. Obviously, the engine makes a decisive contribution to the aircraft's fuel efficiency. The fuel efficiency of the power plant is determined by the level of thermo-gas-dynamic perfection of GTE. Thus, the transition to higher thermodynamic cycle parameters (gas temperature in combustion chamber Tg^* and total pressure increase $\pi^*\kappa\Sigma$), while reducing losses in the elements, provides an increase in internal (thermal) efficiency, and higher bypass ratio (for turbofan engines) contribute to an increase in thrust efficiency [2]. Rise of temperature and pressure in the flow section of the engine requires the use of new materials, aerodynamic shapes and power schemes for GTE structural elements. The solution of these problems is a string of complex problems that are solved by deep research, design and technological study in various fields of science and technology.

The fuel efficiency indices of modern engines were achieved by the transition to new schemes, an increase in the cycle parameters and bypass ratio, the use of new structural materials and technologies. All these measures are aimed at improving the overall efficiency of the engine. Figure 22 shows the historical development of reducing the specific consumption of engines. It also shows the contribution to reducing fuel consumption by the improvement of materials and upgrade of overall parameter ratio (OPR) along with an increase in overall bypass ratio (OBR) and fan pressure ratio (FPR) [3].

It is commonly known that overall efficiency characterizes that of fuel used by the engine in flight. Overall efficiency evaluates the rate of fuel chemical energy converted into effective work. This efficiency considers all the losses in the course of converting heat into effective work.

Meanwhile, aviation GTEs combine the functions of an engine and a propulsion unit. The functions of GTE, as a thermal engine, are to convert fuel chemical energy into an increment of the kinetic energy of the gas stream passing through the engine. As a propulsion unit, the gas turbine engine converts the resulting increment of kinetic energy into useful (traction) work. Engine fuel efficiency, in terms of a thermal engine, is characterized by internal efficiency (thermal efficiency with an ideal cycle). Internal efficiency depends on the degree of pressure ratio in the engine, gas temperature at the combustion chamber outlet, hydraulic losses in the engine passage, and the coefficient of heat emission in the combustion chamber. With regard to a propulsion unit, i.e. a device designed to generate traction force, GTE is characterized by traction efficiency (traction efficiency in this study includes transmission efficiency), which shows what part of kinetic energy acquired by the gas flow in the engine is converted into traction (efficient) work.

Specific fuel consumption, as a characteristic of fuel efficiency, at constant speed decreases with increasing overall efficiency. Overall efficiency, in turn, is the product of internal (thermal) efficiency and traction efficiency.

The stated relationship between efficiency and fuel efficiency of the engine allows us to emphasize the logic of the ways of development of power plants. In other words, further development of power plants, aimed at reducing the specific fuel consumption, will be associated with an increase in internal (thermal) and traction efficiencies. It is convenient to show these ways in graphic form. Figure 23 shows the relationship between the development ways of power plants with specific fuel consumption and efficiency factors.

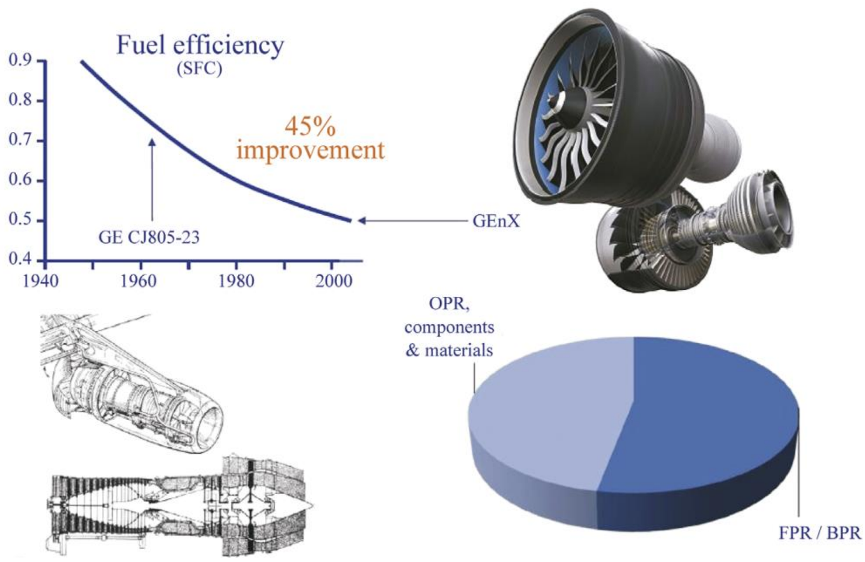


Figure 22. Historical fuel burn improvements

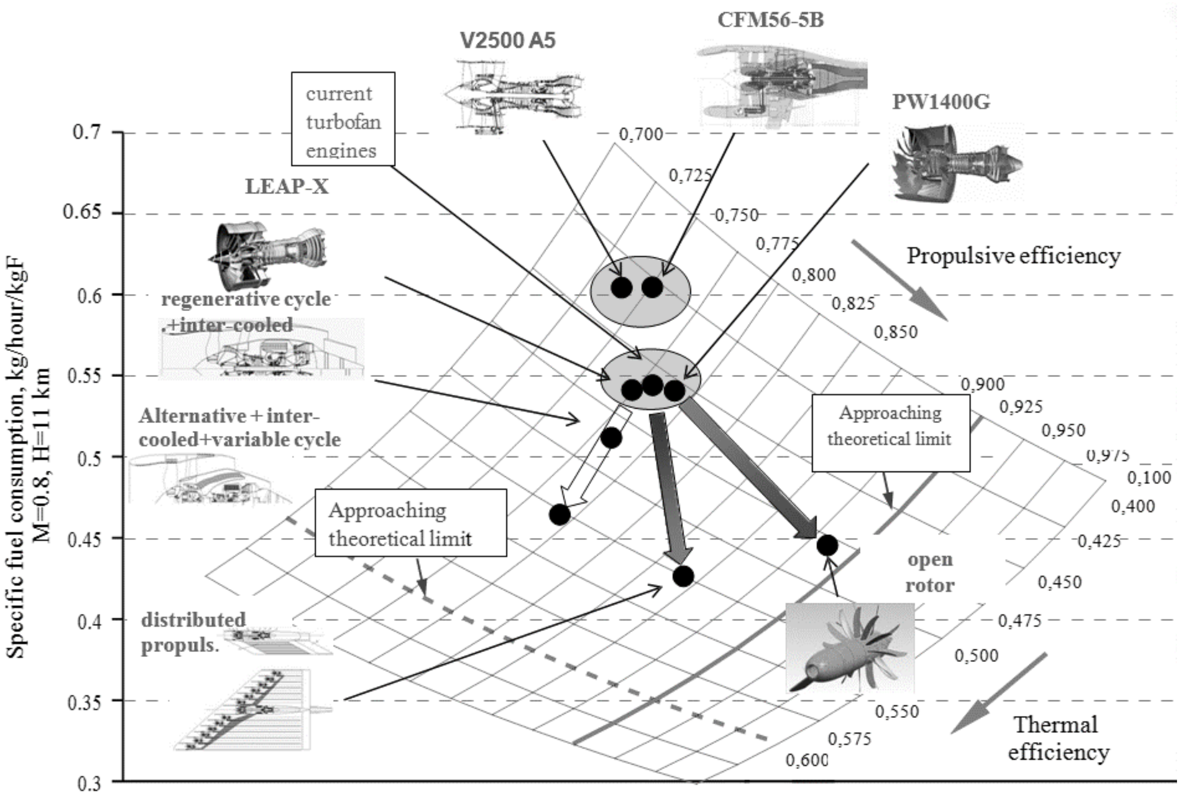


Figure 23. The ways of development of power plants and the relationship with fuel efficiency, traction and thermodynamic efficiency

Figure 23 shows the reduction in fuel consumption of the advanced (at the moment) engines of the LEAP and PW1000G families. One of the main features of these engines is a fan of large diameter. The main requirements for fans of this type include very high performance and efficiency in meeting the stringent requirements for noise and operational safety. Based on these requirements, fan blades of modern engines are of complex spatial configuration without anti-vibration shelves and lightweight design. This required a joint solution to the problems of gas dynamics, strength, materials and production methods.

In addition, along with this, a characteristic feature of modern engine development is the tendency to reduce the number of stages of the turbo-compressor unit in order to cut production and operation costs and to lower engine weight.

Development of new blade machines is aimed at intensifying the working process in separate stages. Currently, techniques of choked-flow single-stage gas generator turbines are widely used, which, together with measures to reduce the number of stages in the compression path, have contributed to wide spreading of compact double-support gas generators, which also contributed to the engine weight improvement [4], [5].

Development rates of aviation GTE are determined primarily by the limitations of gas temperature at turbine inlet acceptable at this stage, taking into account strength, reliability and design life and, thus, directly depend on technologies for creating high-temperature structural materials and cost-effective cooling systems for heat-stressed structural parts. [4]. Reciprocal rise of temperature at high-pressure turbine inlet and specific core power is shown in Figure 24. As it is stated in [3] progressive development to the stoichiometric limit will be difficult, but still possible.

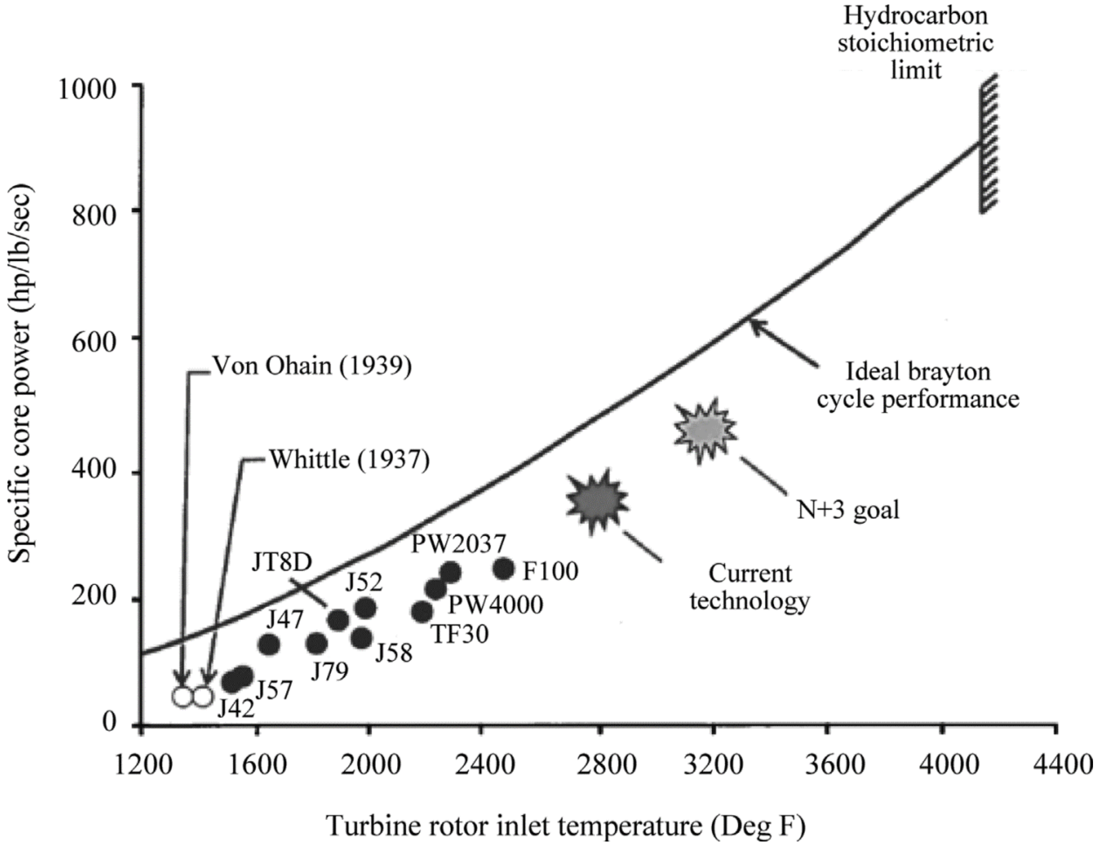
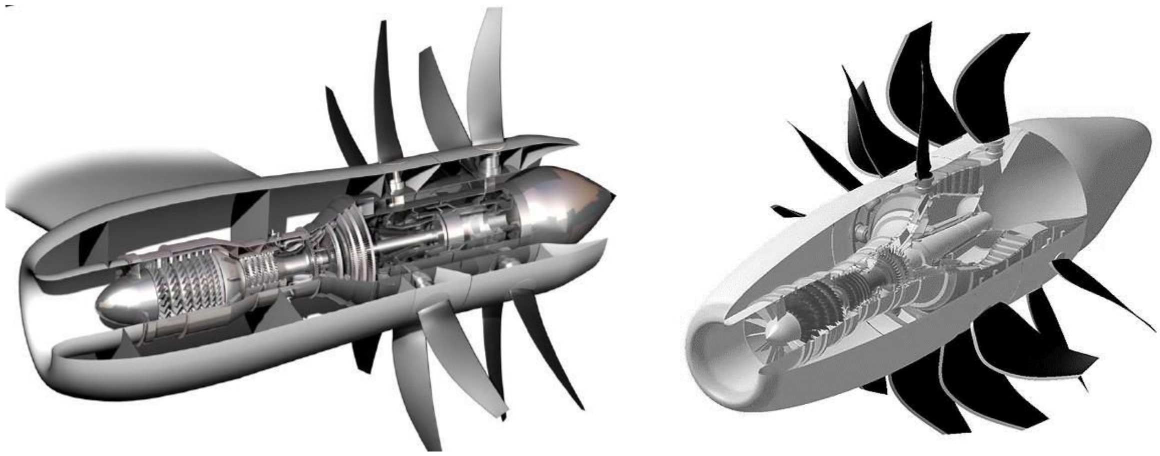


Figure 24. Development of core power and turbine inlet temperature [3]

In future, as fuel combustion approaches the stoichiometric limit, it will be needed to switch to new types of fuel.

Strive to improve bypass ratio in order to upgrade efficiency, to reduce noise and to meet a string of other requirements has led to the up rise of engines with new configurations. Thus, the main distinguishing feature of the PW1000G engine family is a fan-driven by a turbine through a reduction gear. The number of adjustable parameters is increased in such engines, which allows for a wider change in their operational process and better adaptation to flight conditions.

Proceeding from the need to increase bypass ratio of engines further, while limiting the size of the engine nacelle, future advanced configurations are open-rotor engines. With a certain decrease in cruise flight speed, open-rotor engines will have 7.5 to 10% less fuel consumption relative to existing turbofan engines [6]. The advantages of this engine over turbofan engines are that, with equal bypass ratio and the same gas generators, there will be no loss of flow around the cowls of the outer contour. Open rotor configurations can be implemented with a reduction drive (Figure 25a) and with a direct drive (Figure 25b) of the propfan.



a) reduction gear of the propeller b) direct drive of the propeller

Figure 25. Open rotor configuration of the engine with a pushing propeller

Advantages of the direct-drive engine:

- equal moments and powers of the front and rear rows of the propeller;
- simplification of the oil system and oil cooling systems;
- reducing the length of the power plant;
- self-sufficiency of propulsion unit from GG (self-consistent alignment, no skew influence);
- expected reduction in vibration;
- no power limitations.

Expected problems in creating the direct drive of the propeller:

- ultra-low-speed counter-rotating turbine;
- impossibility of separate optimization of the propeller and counter-rotating turbine;
- creation of a reliable mechanism for rotating the propeller blades with minimum dimensions;
- efficient air-gas seal in a counter-rotating turbine on a large radius, etc.
- integration with the airframe.

An open rotor engine, as shown in Figure 23, is most closely located to the theoretical limit of traction efficiency. It should be assumed that the idea of transition to engines of complex (adaptive) thermodynamic cycles would be actively realized in this configuration.

As shown in Figure 23, the purpose of using engines with complex thermodynamic cycles is to increase internal (thermal) efficiency. As an example, let us consider a cycle with intermediate cooling. The diagram of the engine with intermediate cooling is shown in Figure 26, and an example of implementation is shown in Figure 27 [7].

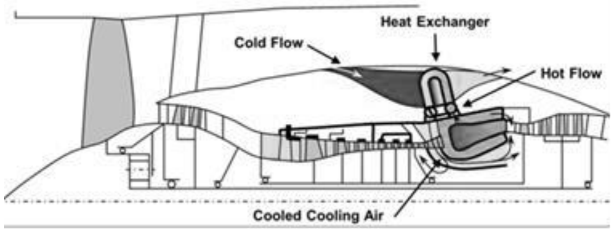


Figure 26. Engine layout with intermediate cooling

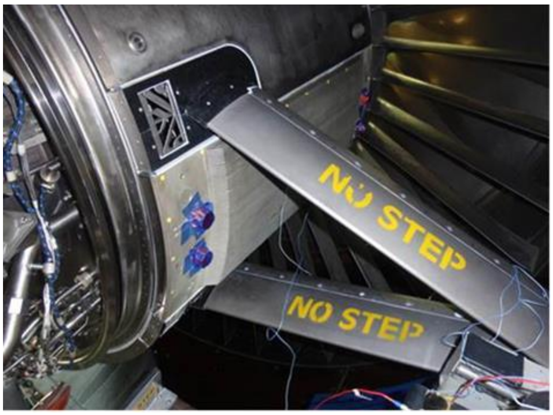


Figure 27. Example of implementation of intermediate cooling by Rolls Royce for an advanced UltraFan engine

As stated in [8] introduction of intermediate cooling under certain configurations provides (depending on the resistance of heat exchangers used) increase by 20 to 22% in the overall thrust of turbofan engines and reduction of specific fuel consumption by 2.5 to 3%.

The main advantage, which the turbofan engine with complex cycle provides, is to obtain the specified characteristics of the engine at low parameters of the operating process. The main problems will be the overall and weight characteristics of the engine with heat transfer systems. Difficulties arise with the creation of efficient, compact and lightweight heat exchangers.

Engines with a large number of controlled parameters or adaptive engines will be the closest to the ultimate thermal efficiency. Control of the inlet section, compressor guide vanes, turbine nozzle guide vanes and core/bypass exhaust nozzles, etc. are expected in these engines.

This will allow changing the parameters of the thermodynamic cycle and bypass ratio in a wide range depending on flight conditions. Although these technologies are being elaborated mainly in the interests of the air force, it is worth presuming that with time, the technologies developed will be transferred to the commercial sector. The diagram of a similar engine and control parameters are shown in Figure 28 [9]. The expected reduction in specific fuel consumption of a variable-cycle engine is shown in Figure 29 [10].

Note that optimal control at various stages of flight and engine operation at the most advantageous parameters of the operating process and bypass ratio will be the advantages of this configuration. The disadvantages of this configuration are an extremely complex system of automatic control of the engine, a large number of mechanisms necessary for controlling the parameters. This will affect the weight perfection of the engine and the level of engine reliability.

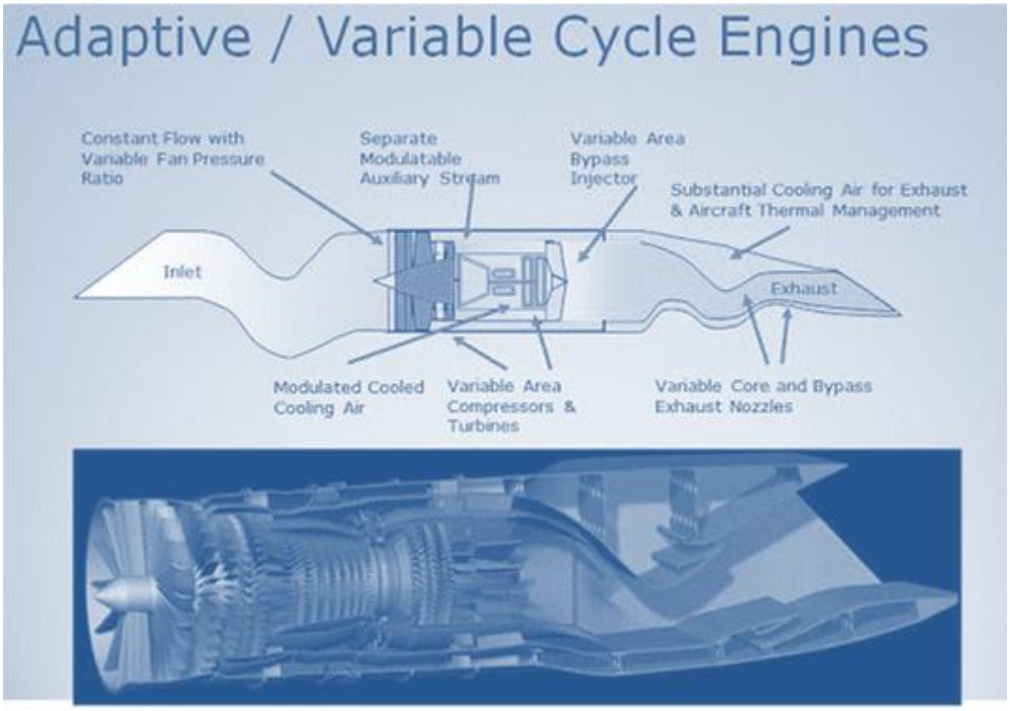


Figure 28. Diagram of the engine with adaptative (variable) cycle

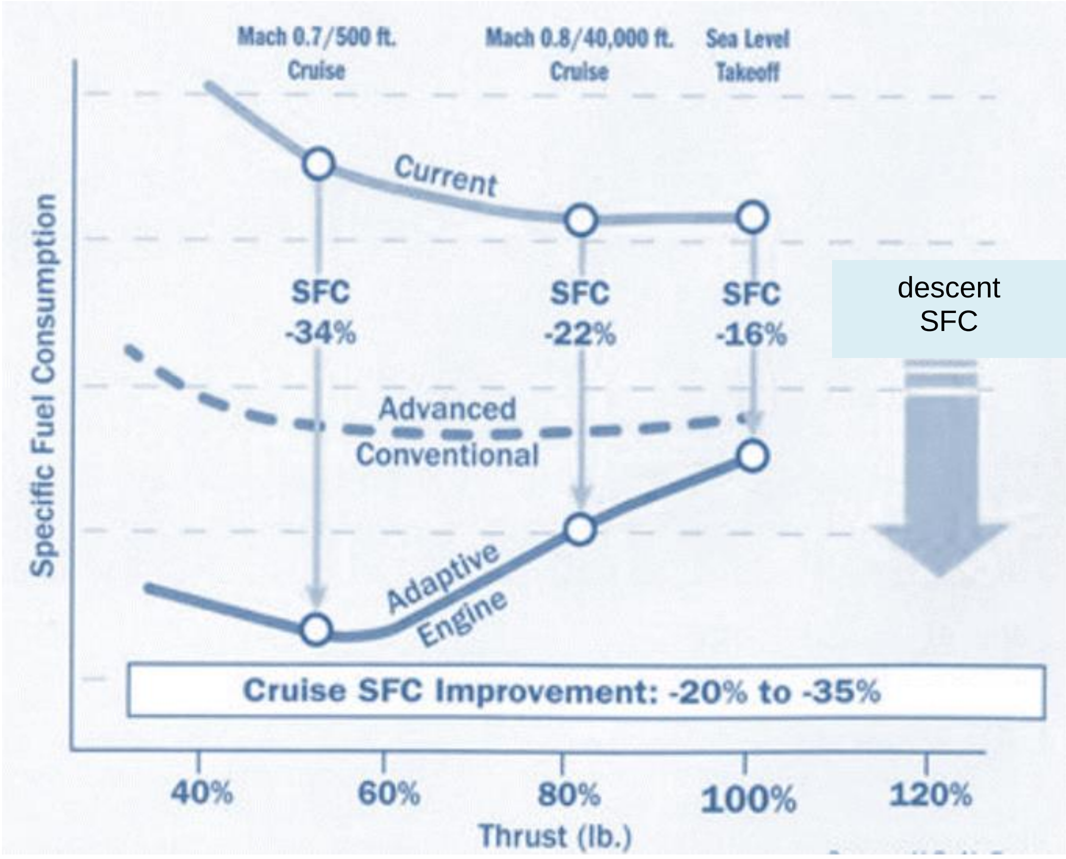


Figure 29. The expected reduction in fuel consumption of the engine with adaptative (variable) cycle

It is also worth noting that the aviation engine, although it is largely determining the fuel efficiency of the aircraft as a whole, in the advanced types of aircraft there are observed processes of deep integration of the airframe and power plant [11]. Based on Figure 23, the most compromise version of the power plant for future aircraft is a distributed power plant. *Some of the concepts are based on the use of distributed small multiple engines, gas-driven multi-fans, mechanically driven multi-fans, cross-flow fans, and electric fans driven by turboelectric generators* [12].

As an example, we show a distributed power plant with a mechanically driven fan from a turbofan engine (Figure 30).

The advantages that the distributed power plant provides are as follows:

- reduction of fuel consumption due to the suction of the boundary layer and filling of the aerodynamic wake created by the airframe, the distributed flow from the power plant;
- better integration of the power plant and airframe, which provides additional noise reduction;
- weight reduction of the power plant due to integration of the inlet section/nozzle/wing;

- ability to use the propulsion units of the power plant to control the aircraft in order to exclude control vanes.

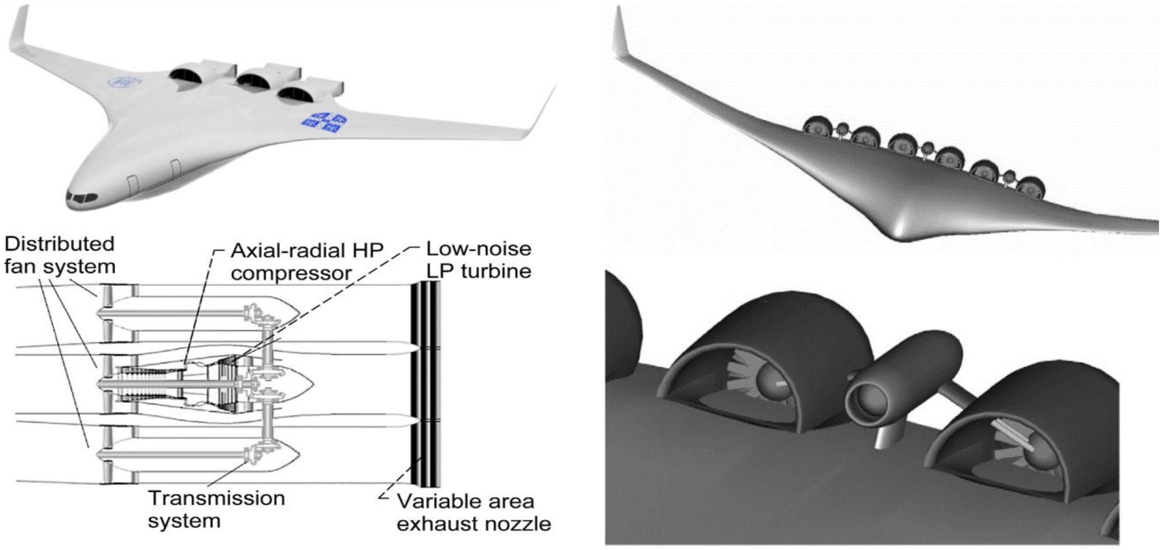


Figure 30. Distributed power plants with a mechanical drive of fans[12]

As a disadvantage, it should be noted the difficulty of ensuring a high factor of recovery of total pressure at the engine inlet, while increasing the angle of attack of the aircraft.

Creation of hybrid and electric distributed power plants that are integrated into the elements of the airframe and provide an increase in aerodynamic characteristics of the aircraft as a whole. This way is complicated by the need to make high capacity, low-mass energy storage devices.

The previously listed ways of development of power plants and the expected time of their emergence are shown in Figure 31 [3].

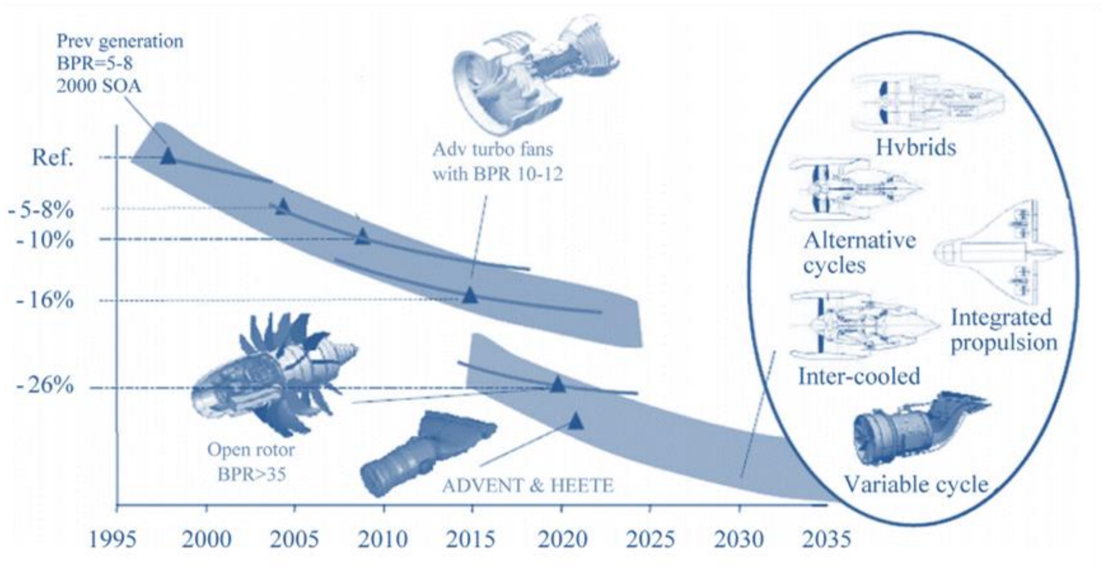


Figure 31. Advanced schemes of power plants with an estimated decrease in fuel consumption and presumable time of commissioning [3]

It should be also noted that a significant increase in bypass ratio of engines and pressure in modern compressors has led to a decrease in the size of the flow section of the engine core, which is particularly manifested in the high-pressure passage. The consequence of reducing the blade heights is the increased negative effect on the efficiency of the radial clearance, the relative thickness of blade edges, deviations of the profile shapes from the nominal ones, etc. These factors contribute to the development and application of radial clearance control techniques to improve engine efficiency.

The analysis performed enables us to conclude that the main ways to improve aircraft power plants for long-haul aircraft for the nearest outlook are:

- rise of gas-dynamic perfection degree of the engine with a simultaneous increase in parameters of the operating process, use of intermediate cooling systems, high-pressure compressors and turbines;
- ensuring the stoichiometric combustion process;
- development of hybrid distributed power plants;
- raise of engine efficiency by increasing bypass ratio and transfer to the open rotor scheme;
- reduction of the specific weight of the power plant through the use of advanced alloys and composite materials, advanced engine architectures, etc.;
- waiving of air bleeding systems from the air-gas path of the engine in favour of electrical systems ("electric engine" technology);
- further integration of the airframe, the engine and their systems.

Also currently, one of the ways to improve fuel efficiency is the modernization of existing engines based on accrued operating experience. In many instances, efforts are aimed at reducing fuel consumption, emissions and noise. One of the examples of further development of the engine for wide-bodied aircraft is the new version of D-18T engine: D-18T of 3M series with improved acoustic performance and low emission. This engine is designed for the world's largest wide-body transport aircraft An-124 "Ruslan" and An-225 "Mriya". The new engine modification has a number of improvements and meets all ICAO environmental requirements and will enable the aircraft to be operated until 2050 [13].

AII.2 Technologies of leading companies

Today, the most commonly encountered engines for passenger and transport aircraft are turbofan engines. The main manufacturers of engines for long-haul aircraft are such companies as:

1. **General Electric Aviation** is represented by the following modern and expected engines:

- **CF6**

Production: 1971-present

Variants: -6, -50, -80

Applications: A300, A310, A330, 747, 767, DC-10, MD-11

- **GE90**

Production: 1995-present

Variants: -76B, -77B, -85B, -90B, -92B, -94B, -110B1, -115B

Application: 777

- **GENX**

Production: 2011-present

Variants: -1B, -2B

Applications: 747-8, 787

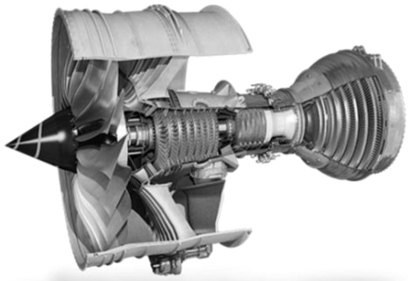
- **GE9X**

Production: due in 2020

Applications: 777-8X/9X

Aircraft on order: 326

2. ***Rolls–Royce*** for wide-body aircraft is represented mainly by engines of the Trent family:



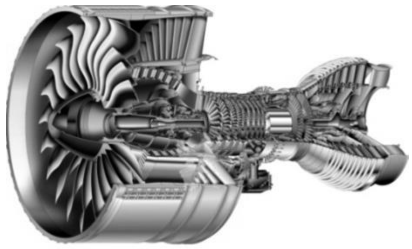
Production: 1995-present

Variants: -500, -700, -800, -900, -1000, -XWB, -7000

Applications: A330, A330neo, A340, A350, A380, 777, 787

3. ***Engine Alliance*** is represented mainly by engines of the

GP7200 family

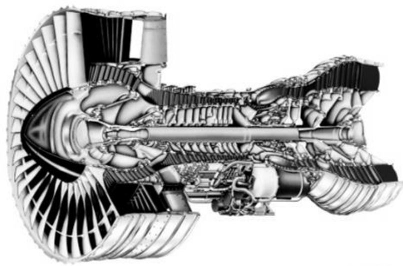


Production: 2008-present

Variants: -7270, -7277

Applications: A380

4. ***Pratt & Whitney*** manufactures versions of **PW4000** engine family for long-haul aircraft



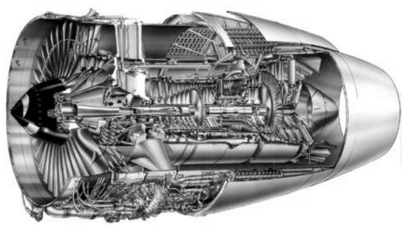
Production: 1987-present

Variants: -94, -100, -112

Applications: A300, A310, A330, 747, 767, 777, MD-11

5. ***ODK-Aviadvigatel*** is represented by **PS-90 engine family**

PS-90



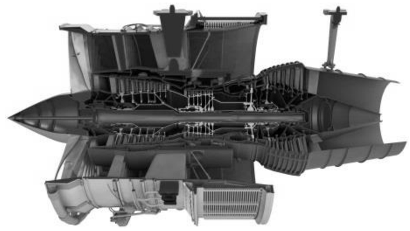
Production: 1992-present

Variants: A, A-76, A1, A2, A-42, A3

Applications: Il-76, Il-96, Tu-204

6. ***Ivchenko-Progress*** is represented by **D-18T** engine family

Д-18Т



Production: 1984-present

Variants: 1, 3, 3M

Applications: An-124, An-124-100, An-124-111, An-225

The ranges of the engine thrust are shown graphically in Figure 32. As can be seen from the data stated, modern engines of supposed engine suppliers do not fit the specified range of engine thrust required for Boeing NMA. Since the engines that fit the thrust class for the expected aircraft were commissioned from 1970 till 1980, it is possible to assume that they will not be used on the newest aircraft. It is expedient to consider further generations of engines and solutions mastered on them. At the same time, Rolls Royce RB 211 engine architecture is the basis for the Trent engine family, which in turn is the basis for the Rolls Royce Advance family. Thus, consideration of modern engines and statements about the best practice and technologies of the expected Rolls Royce Advance and General Electric GE9X will reflect the architecture of the base engines, which are taken as a foundation.

To ensure market leadership, GE takes an active part in research programs. The result of this is competitive engines, which have margins against restrictions of regulatory authorities on the emission of harmful substances and noise produced, acting at the time of market launch of the engine. The company also actively strives to satisfy the allowances of Chapter 4 of ICAO and CAEP 6. The company's links with research programs are shown in Figure 33.

GE's participation in research program NASA E^3 made possible to master technical solutions, which became the basis for creating engines of the GE90 family. The key was the bypass ratio of the engine equal to m = 9. Ensuring a high bypass ratio was achieved by using a fan with straight blades made of composite material in the first engine variants. It was the first engine in the history of commercial aviation with blades of such type. In further GE versions (-110B and -115B), the fan was provided with the modified wide-chord vanes of the rotor wheel with a sweep (variable by height) of polymer composite material shown in Figure 34 [15]. These solutions made possible to reduce the fan noise level and prolong design durability.

Gas generator designed for GE90 became the basis for the entire family and further development of the company's new engines. This solution has ensured the continuity of the design to achieve higher reliability and lower engine maintenance costs. When developing new engine variants, new technical solutions were developed, new materials were used, new blades for units of the hot and cold parts of the engine passage were designed with new 3D calculation methods. Thus, the GE90-115B engine that became the most powerful jet engine in the world was provided with the following distinctive features and technical solutions [5]:

- new fan with a larger diameter (D_f = 3.25 m) and frontal performance with wide chord vanes of the rotor wheel fitted with a sweep variable by height made of polymer composite material;

- a middle shaft of the fan-made of a steel alloy GE1014, which has -15% higher torsional strength, which made it possible to keep its diameter while increasing the transmitted power and eliminated the need to change the parts of the gas generator;
- 4-stage LPC with a device for removal of foreign objects, eliminating their ingress to HPC inlet;
- high-performance 9-stage HPC, designed for pressure ratio π^*_C ~ 18-19, with increased airflow and adjustable IGV and SGV blades of the first three stages, which control program is optimized to ensure high gas-dynamic stability margins; new low-emission two-tier combustion chamber with improved emission characteristics;
- new materials and protective coatings in HPT with an improved cooling scheme for NGV and RW blades, ensuring operability at a higher gas temperature at turbine inlet;
- design "propulsor", providing replacement of the gas generator, LPC and LPT without removing the fan casing from the wing;
- the low emission combustion chamber of DAC type;
- application of new 3D calculation methods for the design of blade machines.

The GEnx engine family was developed to replace the CF6 engine based on GE90 engine. Based on the proven GE90 architecture, the GEnx engine provides up to 15% improved fuel efficiency and 15% less CO2 compared to the GE CF6 engine. The GEnx engine is a breakthrough in materials and design processes that reduce weight, improve performance and create a more economical engine for commercial aircraft [16].

Among the innovative features of the GEnx is a dual-circuit pre-combustion chamber (TAPS) that will significantly reduce NOx emissions and larger and more efficient fan blades. The GEnx engine is also the world's first commercial jet engine with a front fan casing and carbon-fibre fan blades. Composite fan blades on a GEnx engine feature a new, more efficient design with a reduced number of blades (from 22 to 18 fan blades) and a composite fan casing to reduce weight further (Figure 35, left).

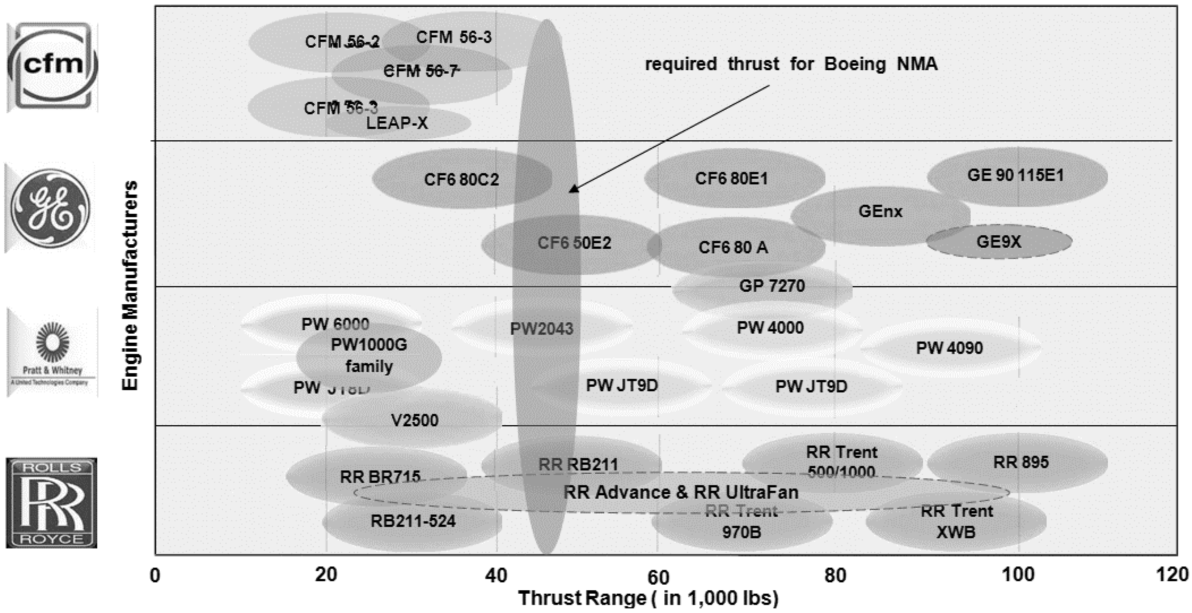


Figure 32. Thrust ranges of engines of various manufacturers, as well as advertised engines (circled by dotted lines)

AI.1.1 General Electric Aviation

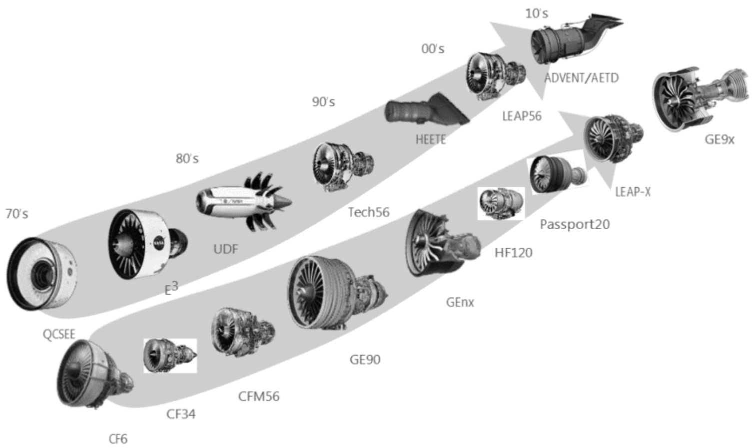


Figure 33. Links of GE engines with research programs [14]

Figure 34. Fan and blade of engine GE90-115B

Figure 35. Carbon fibre composite fan blades and advanced low-pressure turbine (LPT)

The next distinctive feature of the engine is an advanced low-pressure turbine (Figure 35, right). The low-pressure turbine GEnx is lighter and more efficient than its predecessor is and includes 3D aerodynamics of the next generation. Blades of stages 6 and 7 consists of titanium aluminide, reducing the weight of the engine by about 400 pounds (about 181 kg), which contributes to improved fuel efficiency in GEnx engine [16].

It is also essential that engine GEnx-1B was created for Boeing 787, which was designed on the principle of "more electric aircraft" and in the engines, there is no air bleeding due to the compressor that also reduces fuel consumption. As a result, it should be noted that compared to CF6 the GEnX-1B turbofan with parts less by 30%, provides an improvement in fuel efficiency by -15% and an increase in operating time on the wing by -20% that can significantly reduce maintenance costs. In addition, it has excellent emission characteristics (NOx margin by -58%, CO by -90%, HC by -98% and smoke - 95% relative to the ICAO CAEP6 standards) and is the quietest among company engines[16].

It is expedient to consider the engine GP 7200 of joint venture Engine Alliance, the main founders of which are General Electric and Pratt & Whitney. It implements technical solutions obtained in the course of work on the elaboration of advanced technologies, in which General Electric and Pratt & Whitney took part, providing a high level of performance and reliability for the new generation of long-haul aircraft.

The main features of the engine family are (Figure 36):

- single-stage fan with 24 lightweight wide-chord vanes with a variable-sweep by height and a body made of titanium alloy;

- low-pressure spool is based on PW4000 engine, namely, a 5-stage LPC, in which the first stage with swept-forward wide chord blades has a blisc design, and the 6-stage LPT, which blades are made of new single-crystal alloy LEK94 having a specific gravity less by 7 % than traditional nickel alloys;

- gas generator is based on GE90-115B with a low-emission single-staged chamber; 2-stage high-pressure turbine, in which new single-crystal nickel-cobalt alloy N5+ (for blades) and powder alloy ME3 (for disks) are used, which have high-temperature strength and heat resistance;

- ACS FADEC III + developed jointly by companies General Electric and Pratt & Whitney, which has a speed-of-response -16 times faster and memory 10 times bigger than existing ACS, with a built-in system for diagnosing and monitoring the technical condition of the engine;

- accessory box mounted on the gas generator housing.

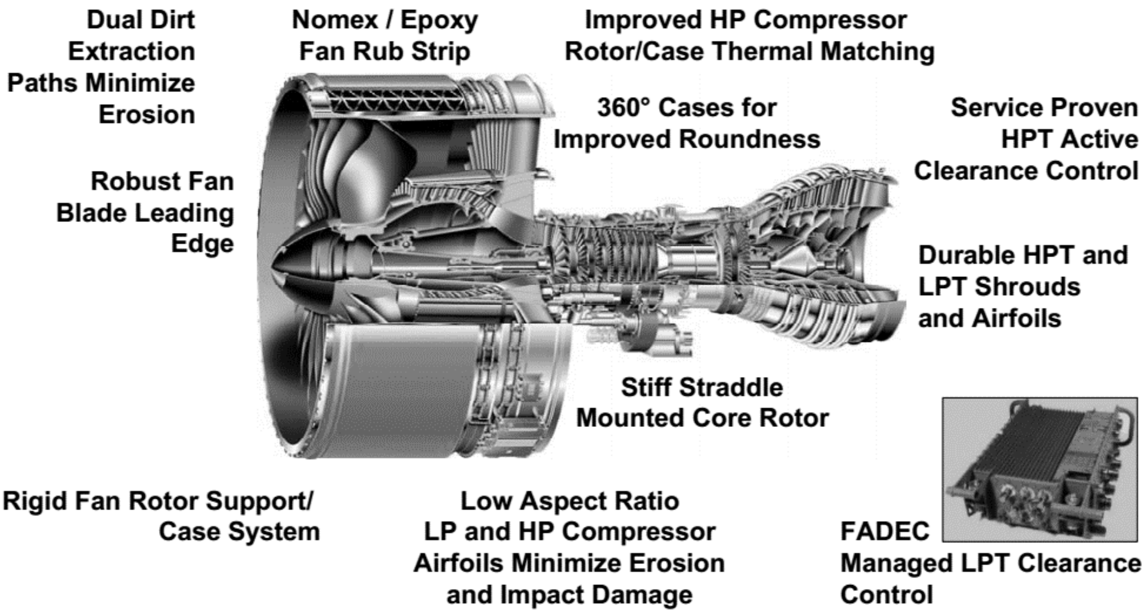


Figure 36. Technical solutions implemented in GP7200 [17]

The next key step in developing new solutions for creating GE9X for GE is the CFM International LEAP project. CFM International is a joint venture of GE and Safran Aircraft Engines in equal shares. This company is in a unique position. On the one hand, Safran provides access to European technologies and GE to US technologies. An example of successful cooperation is the development and production of the CFM-56 engine in equal parts. CFM-56 engines have thrust from 82 to 151 kN. Both companies joined in concern CFM are responsible for the production of different engine components, each of which has its own final assembly line. GE is responsible for the high-pressure compressor, the combustion chamber and the high-pressure turbine, Safran is responsible for the fan, the low-pressure turbine and the gearbox.

The company is also responsible for the development, maturation and production of the fan module in the LEAP engine as well.

Hence, it should be assumed that the technologies developed on the LEAP engine family will be implemented in GE advanced developments. As stated in [18] engine fuel consumption is reduced by 15% compared to CFM56. Aerodynamically efficient 3D woven fan blades of LEAP engine are made of carbon fibre composite RTM (Resin Transfer Moulding) 3D, the first in the industry for CFM. This technology leads to the fact that the fan blades are light and durable. The LEAP engine shows a 15% reduction in fuel consumption, compared with its predecessor, through the use of blisk-turbine in the compressor, second-generation combustion chambers with double annular flow pre-mixing (TAPS II), ceramic matrix composites (CMC) for turbine housings and bypass ratio about 10-11 (Figure 37). In addition, advanced three-dimensional 3-D aerodynamic design techniques were used for low-pressure section blades and new, stronger, lighter alloys such as titanium aluminide (TiAl) and high-strength steel for high-temperature ML340 were applied.

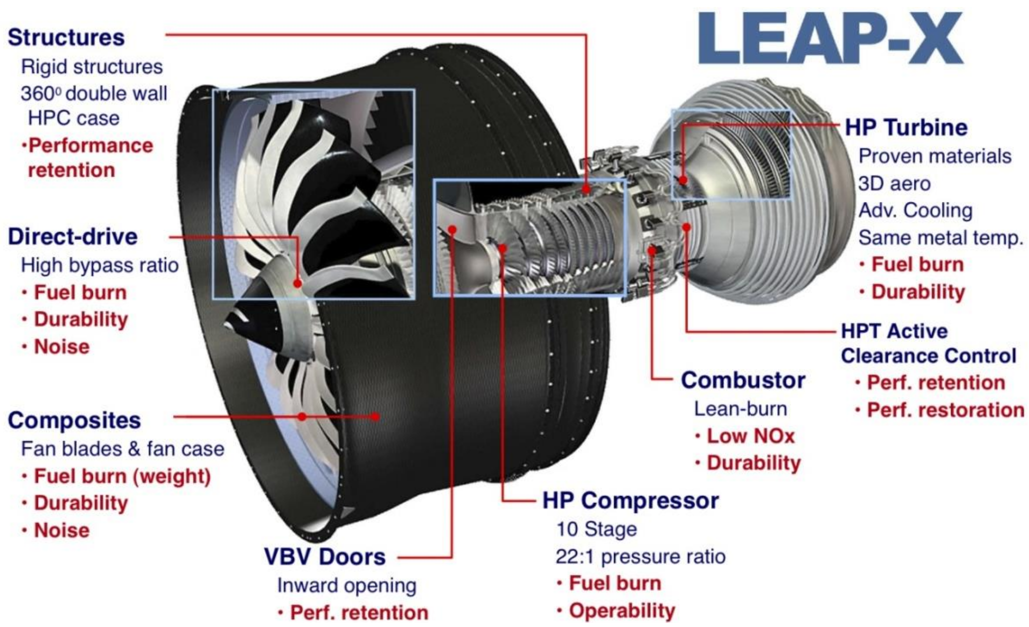


Figure 37. Technologies applied in the LEAP engine

One of the first cases in the history of civil aviation is the use of parts in the design of an engine printed on a 3D printer (Figure 38). As stated in [18] the nozzle is lighter by 25% than the previous model and 5 times more durable. Developing thrust from 28,000 to 34,000 pounds, the LEAP engine provides significant efficiency gains for next generation commercial aircraft: reducing CO_2 consumption by 15% compared to existing engines, reducing NO_X emissions by 50%, and complying with the most stringent noise programs (chapter 4 of the ICAO program)[19].

Figure 38. 3-D printed nozzie

Attention is drawn to the fact that LEAP engines are designed to power medium-haul narrow-body aircraft, but at the same time, this program will help GE to work out and implement technical solutions that will be used in the advanced GE9X. Since the engine GE9X reportedly [Commercial engines. Turbofan focus, 2018, Flight global] entered the stage of flight tests in 2018, let us consider the evolution of the basic elements of engine design. Application of 3D aerodynamic calculation methods, composite materials and new production methods resulted in the creation of wide-chord fan blades with a variable sweep, which leads to a decrease in the number of blades and an increase in fan efficiency. The development of this direction is shown in Figure 39. It should be assumed that the company would apply the experience gained in this area to open-rotor engines, as well as for distributed power plants of various types.

Figure 39. Fan blade development in GE engines

Figure 40 shows the improvement of the engine compressor. As stated in [14], improvements made for GE9X will reduce specific fuel consumption by 2%. The low-pressure compressor is a three-stage one, and the number of stages in the high-pressure compressor has been increased to 11, with the first five of them being made using the blisk technology. The compression ratio in HPC increased to 27, and the total pressure increase in the GE9X reaches a record 60.

Figure 40. Development of compressor technology by GE company

The combustion chamber complies with class TAPS III and provides a qualitative reduction of harmful emissions (Figure 41). The coatings of the combustion chamber and the blades of a two-stage high-pressure turbine are made of composite materials based on the ceramic matrix, having the strength twice higher, weight three times less and heat resistance considerably better than traditional metal ones. The blades of the six-stage low-pressure turbine are made of titanium aluminide so that they are stronger, lighter and more durable than nickel ones.

Figure 41. GE's combustion chamber technology development

Mastered and new technologies now are used in the GE9X engine. Engine certification is expected during 2019-2020. The engine is supposed to replace the GE90 family. The future production version of the GE9X - 105B1A is designed for takeoff thrust of 47.7 to and should be by 10% more economical than the current GE90-115.

At the same time, the GE9X and LEAP-X engines are the most likely platforms for engine development for the offered Boeing NMA aircraft. Since the required new engine should be more economical, the disadvantages of these engines include the absence of a fan reduction drive. In addition, the engine thrust level is either too high (GE9X) or too low (LEAP-X).

AII.2.1 Rolls-Royce

Rolls Royce is represented on the mainline aircraft market by the Trent engine family, which includes Trent 500, 700, 800, 900 series, the newest Trent 1000, Trent 1000 TEN, and Trent XWB expected soon after 2020 Advance [20]. The basis of the Trent family is the three-shaft scheme RB211. Due to innovative technologies and a three-shaft architecture, Trent engines provide individual scaling of high, medium and low-pressure systems in comparison with existing structures, ensuring maximum operational flexibility. This achieves lower design costs providing optimized high-performance engines for applications on specific aircraft with class-leading economic indices, which are primarily designed to minimize environmental impact.

The Trent 700 was specifically designed for Airbus A330 and was the first engine in the Trent family. With the introduction of a diffusion-bonded/super-ductile (DB/SPF) broadband fan to Trent 700, Rolls-Royce has achieved technological success on all Trent engines. Three-dimensional aerodynamics and tiled composite combustion chambers were introduced to improve durability and lower operating costs for the Trent 500 and Trent 900.

Further development of the Trent 900 is the Trent 1000 with the use of new technical solutions from the program for developing advanced Vision technologies of Rolls Royce. Engine design features are (Figure 42) [21]:

- single-stage low-noise low-speed fan with a diameter of D_f = 2.845 m with 20 RW wide-chord lightweight vanes made of a titanium alloy with a variable sweep, improved aerodynamic characteristics and a low value of the relative diameter of the hub;
- a power off-take device from the shaft of the medium pressure shaft (Intermediate Pressure power off-take), on which two starter-generators with the power of N_{ft} = 250 kVA are installed, which ensure the engine start and supply of electricity to the aircraft systems;
- new nickel alloys and technologies for the manufacture of HPC and LPT blades, ensuring an increase in engine life;
- low-emission single-staged annular combustion chamber of a "tiled" design with direct fuel injection and a lean combustion zone;
- counter-rotation of high and medium pressure rotors;
- intelligent sensors in ACS and technical condition diagnostic system.

Application of a fan with a low value of the relative diameter of the hub in propfan Trent 1000 provides a reduction in weight, external resistance and fuel costs. The applied design of the blades of the fan impeller provides low weight, good aerodynamic characteristics and resistance to ingress of foreign objects. The outlet guide vanes also have lightweight arrow-shaped vanes and for their manufacture, the same technological process is used as for the blades of the rotor wheel.

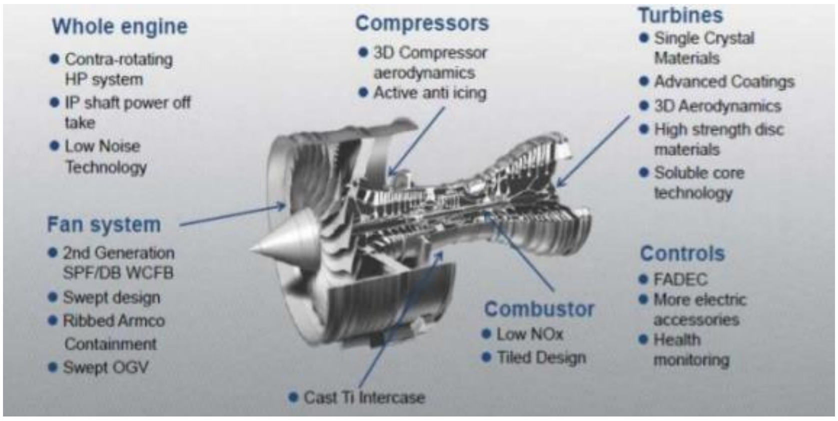


Figure 42. Technologies applied in the Trent 1000 engine

Due to the hydraulic coupling used in the device for power take-off from the shaft of the medium-pressure spool, the Trent 1000 engine spins both spools - the medium-pressure spool and high-pressure spool, when the engine is started, resulting in a starting time of less than 40 s. In flight conditions, the power take-off for the generator drive is made mechanically from the shaft of the medium-pressure spool. Generators of each engine can output up to 0.5 MW of electricity for the electrical systems of the aircraft B787. The use of the device for power take-off from the medium-pressure spool shaft makes possible to [22]:

- reduce fuel consumption up to -6% on short routes and 1 - 1.25% specific fuel consumption in terms of cruise flight relatively to the engine with power off-take from HPC;
- reduce thrust at ground idle that favourably affects the reduction of fuel consumption, noise and load on the landing gear brakes;
- reduce the time of the transition process from the ground idle to the maximum due to the higher value of the HPC gas-dynamic stability margin;
- increase the margin of HPC gas-dynamic stability;
- reduce operating costs.

Elevated pressures and temperatures in the combustion chamber result in an undesirable increase in NOx emissions. The rate of NOx formation grows with the temperature of the fluids, reaching peaks at an air-fuel ratio close to stoichiometric. Therefore, at low NOx emissions, the time consumed on combustion of the mixture at high temperatures should be minimized. The combined Phase 5 RR combustion chamber technology used in the Trent engine family successfully optimizes this approach for controlling NOx well below current levels of legislation [23].

Further development of the Trent family today is the Trent XWB engine (Figure 43). According to the company, this engine is the most efficient engine in the world as part of the Airbus A350 power plant [24].

The main features of Trent XWB are as follows:

- three-shaft engine configuration, which provides less weight of the structure;
- the fan has a diameter of just under 3 meters with wide-chord profiled blades;
- compressor and turbine blades are calculated using the latest methods of 3D aerodynamics;
- 1 3 steps of the high-pressure compressor are made by blisk technology;
- 2-stage high-pressure turbine;
- monitor systems for rotor radial clearances.

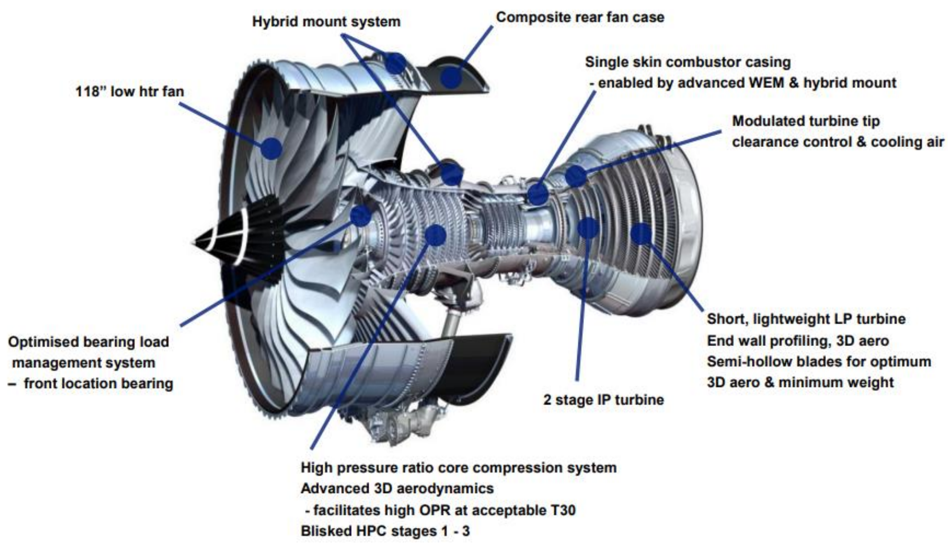


Figure 43. Technologies applied in engine Trent XWB[25]

Trent 7000 is an engine developed by Rolls-Royce exclusively for Airbus A330neo, based on the architecture and technology of Trent 1000 and Trent XWB, respectively, will replace Trent 700 - the market leader in its category. Trent 7000 is the latest engine certified by the company. The main features of the engine are shown in Figure 44.

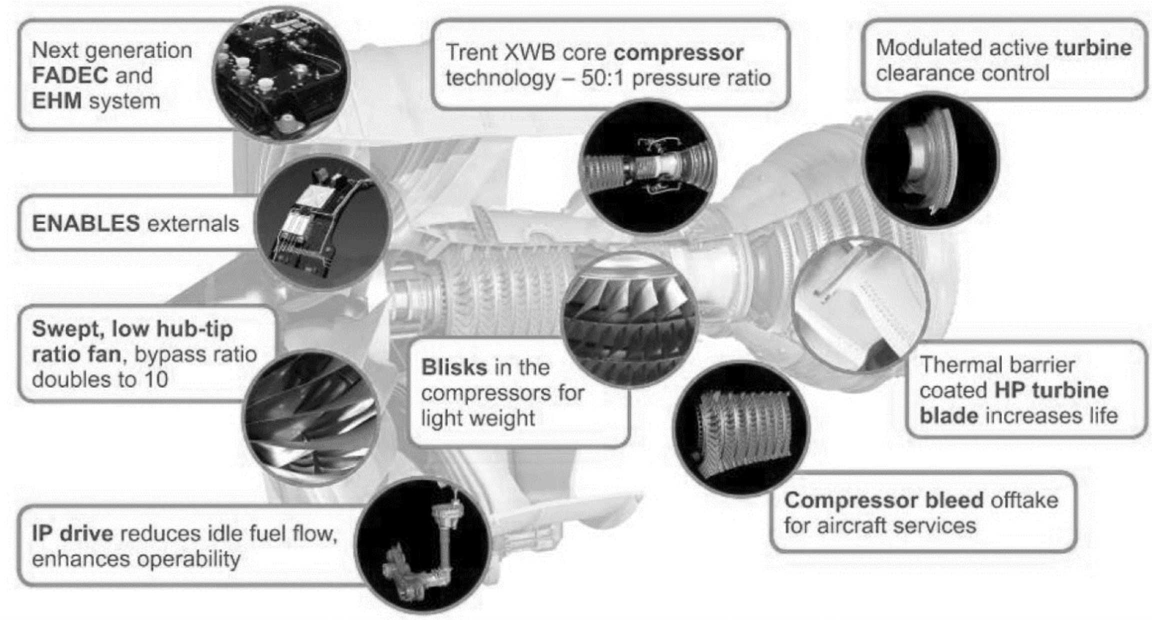
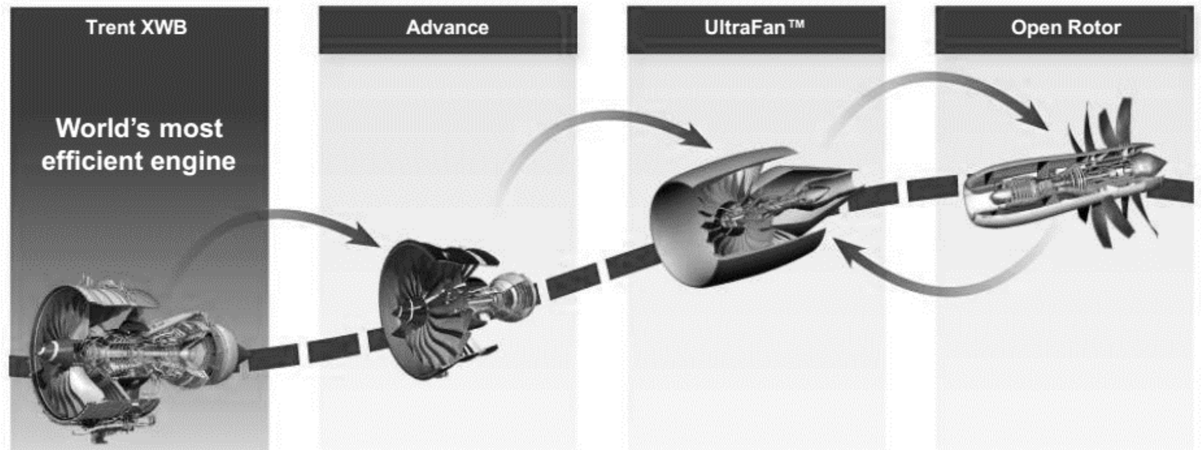


Figure 44. Features of engine Rolls Royce Trent 7000

Further direction of the company's development is shown in Figure 45. As can be seen from the shown diagram on the basis of the Trent XWB engine, the company expects to produce the following generations of engines of the Advance type (for wide-bodied long-haul aircraft it is Advance 3) [26].



Technology EIS Readiness	2020+	2025+	Airframe Dependant
Bypass Ratio	11:1+	15:1+	50:1+
Overall Pressure Ratio	60:1+	70:1+	70:1+
Eff relative to Trent 700	20%+	25%+	30%+

Figure 45. The direction of development of the engine company Rolls Royce

New engines planned by RR reflect the latest trends of the power plant including the steadily increasing thrust efficiency to be achieved by fans of larger diameter, by higher bypass ratio and smaller engine parts. A big change in Advance is a nucleus that "redistributes the workload" between medium and high-pressure compressors and turbines (IPC / HPC and IPT/ HPT). This decision will be the basis for future generations of engines. The Advance engine covers a collection of new technologies designed to improve thermodynamic efficiency. The Advance will be equipped with such innovative technologies and solutions:

- lightweight, highly efficient compressors and turbines as well as fans made of carbon-titanium CTi;
- advanced cycle with a higher-pressure ratio;
- cooled turbine made of ceramic composite materials;
- smart adaptive systems and adaptive cooling;
- hybrid ceramic bearings;
- combustion chamber with low emissions of nitric oxide (NOx).

According to RR, Advance's engine will employ the "unique" turbine architecture with direct fan drive. This will be achieved as a result of several years of research in the field of new technologies. The design is expected, which should have a bypass ratio of more than 11: 1 and a total pressure ratio of more than 60. The expected date of commissioning is soon after 2020 [27]–[29].

RR expects UltraFan as the next generation of engines after Advance (Figure 46). UltraFan retains the Advance gas generator when a multi-stage turbine is introduced with reduction gear for driving the fan and compressor. Based on these characteristics, the main change in UltraFan is the reduction gear to lower the fan speed. It is expected that UltraFan will have a bypass ratio 15 and a total pressure ratio of more than 70. The main distinctive features of UltraFan will be (Figure 46)[27]–[30]:

- an advanced fan with carbon and titanium (CTi) composite fan blades for a new generation of engines with variable pitch angle;
- hybrid ceramic bearings;
- built-in "thin" nacelle;
- disk ("blisk") and ring compressors;
- wider use of ceramic matrix composites (CMC), including titanium aluminide (Ti-Al)/CMC high-pressure turbine blades.

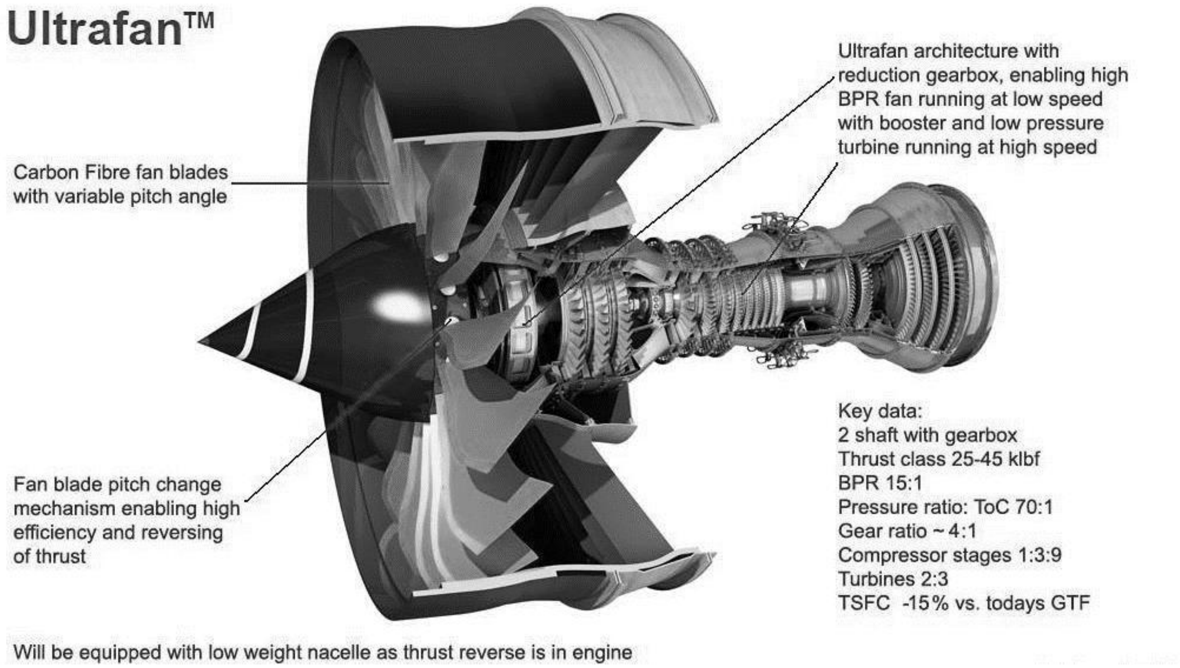


Figure 46. The project of engine UltraFan

The company presumes that, compared with the Trent 700, which powers Airbus A330, the Advance and UltraFan engines will provide a "significant increase in efficiency" - by more than 20% and 25%, respectively. UltraFan should be a footstep to an open rotor design. It is also expected that in these engines the number of parts made by additive production (more commonly known as 3D printing) will grow. Initial results show the excellent performance of parts made by 3D printing, as well as of ceramic matrix composites. 3D printing enables engineers to create new parts designs that are faster and cheaper to produce[28].

The directions of research and necessary key (critical) technologies that Rolls Royce aims at are shown in Figure 47 and Figure 48 respectively.

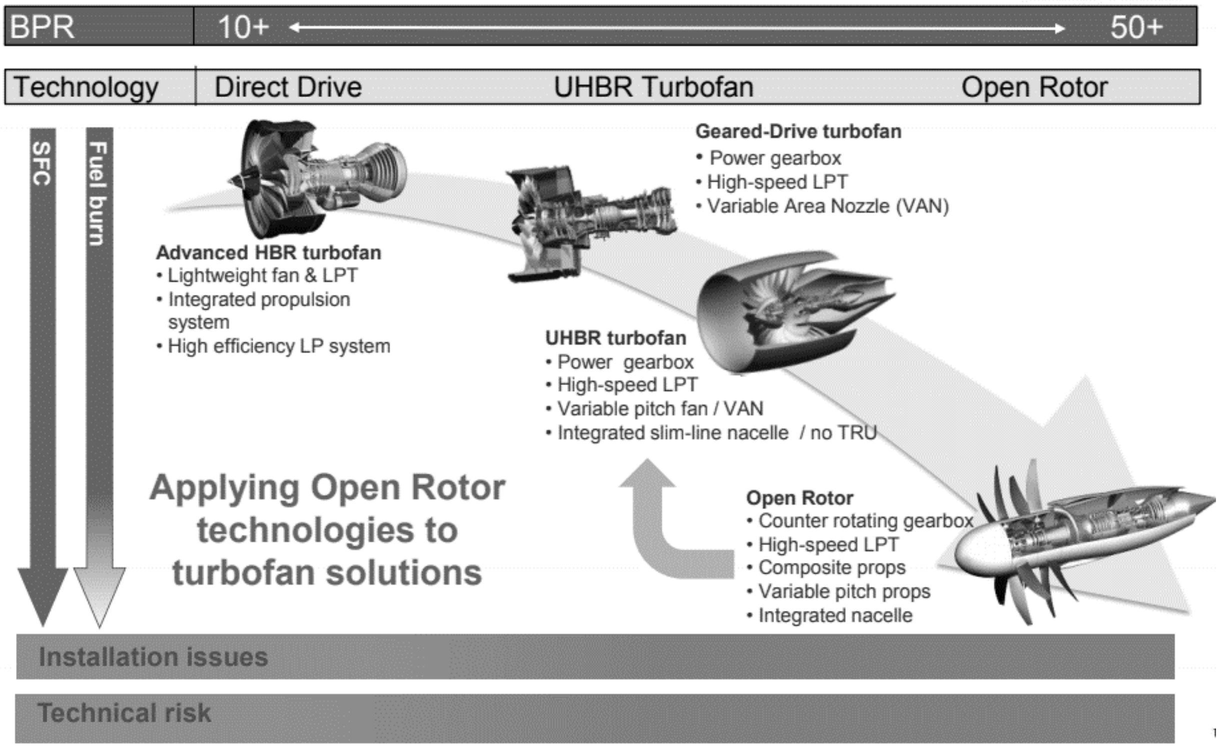


Figure 47. Advanced configurations of the engines reviewed by Rolls Royce

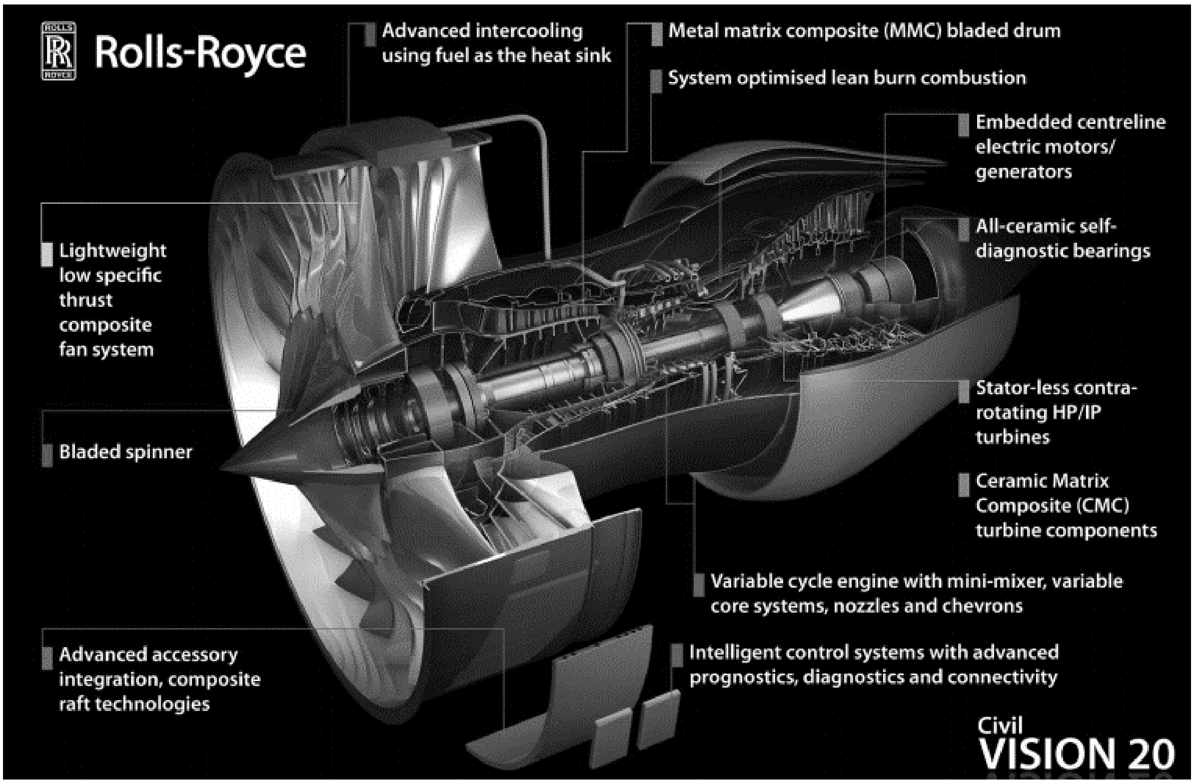


Figure 48. Critical technologies developed by Rolls Royce in the framework of program Vision 20

Expanding the use of electrical technology in future aircraft and engines will also benefit. Aircraft and engine systems such as aerodynamic control drives, brakes, fuel metering systems, etc., are traditionally a mixture of hydraulic and pneumatic systems. Many of them, such as cabin air conditioning systems that run on compressed air directly supplied from engine compressors, can be replaced with special, lighter and more energy-efficient electrical equipment. Built-in electrical generators can withstand large electrical loads. Sustainable management of this electrical load can also offer opportunities for improving the engine. More electric motor technologies will reduce fuel consumption by 2% along with other operational benefits: maintenance and reliability [23].

AII.2.2 Pratt & Whitney

Pratt & Whitney's work on creating and commissioning the Pure Power PW1100G engine family has had a significant impact on the development of turbofan engines. The technical solutions implemented in this engine family are shown in Figure 49.

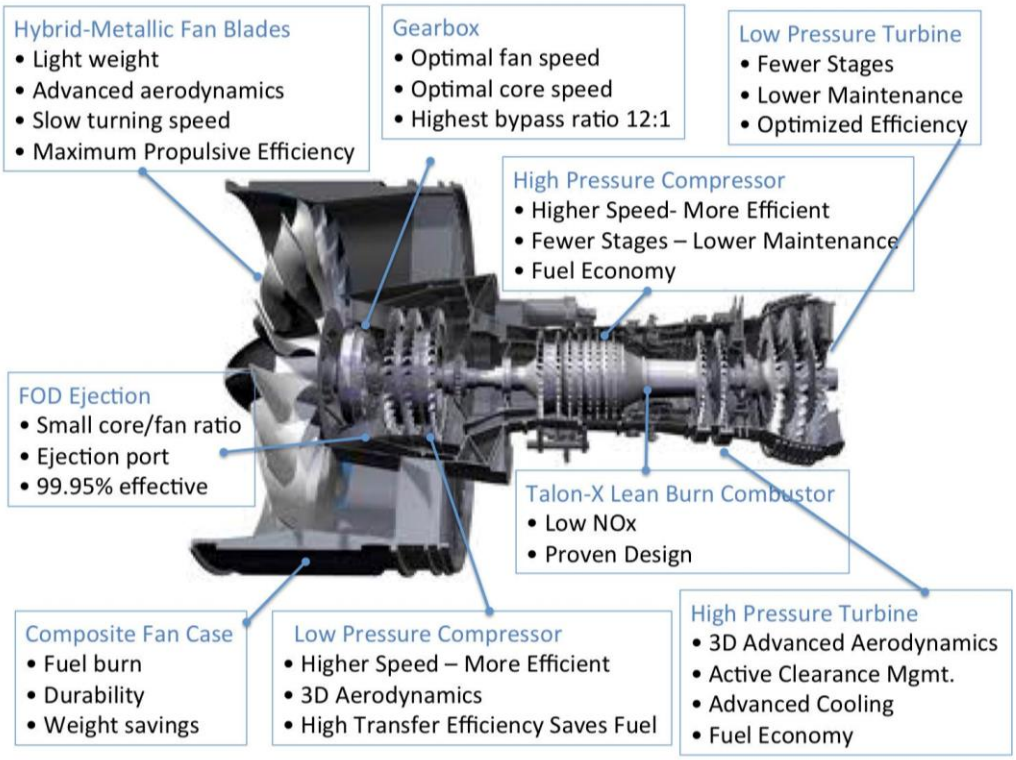


Figure 49. Technologies of Engine Family PW1000G

This family of Pratt & Whitney turbofan engines has a high bypass ratio. One of the main distinguishing features of the engine is the fan drive through a reduction gear of a planetary type (Figure 50), which enables the engine fan and the low-pressure spool to operate at more favourable rotational frequencies. The difference in speeds increases engine efficiency and reduces fuel consumption, emissions and noise. In addition, the planetary gear reduces the number of stages of the gas generator and engine parts that reduces the weight of the engine and the cost of its maintenance.

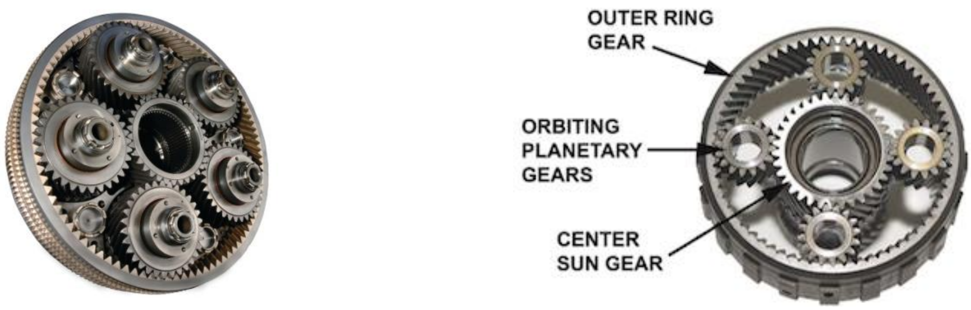


Figure 50. Pratt & Whitney Gear Box [31]

The GTF engine complies with all specifications from the time of commissioning. For example, the GTF-powered A320neo achieved a 16% reduction in fuel consumption, a 75% reduction in noise and a 50% reduction in nitrogen oxide emissions[31].

In September 2015, the FAA (The Federal Aviation Administration) announced that Pratt & Whitney was selected to participate in the program, which should lead to a reduction in fuel consumption and emissions in the second phase of the FAA initiative "Permanent reduction of energy, emissions and noise" (CLEEN II) [32]. To this end, Pratt & Whitney will continue to use advanced technologies that are applied to develop a Pure Power engine with a high bypass ratio and fitted with a GTF gearbox. In particular, these works will be aimed at improving the thermal efficiency of the engine core.

One of the ways to improve fuel efficiency, which are used by designers, is to increase the bypass ratio. The PW1100G engine has a bypass ratio of 12.2. Pratt & Whitney is currently working on the next generation turbofan engine with the bypass ratio, which the company describes as "significantly higher" than 12.2, as was in the PW1100G engine, for the expected middle-class aircraft. The engine being developed will become a competitor to CFM International LEAP and conceptual Rolls-Royce UltraFan.

Pratt & Whitney is also working with NASA on the New Horizons initiative.[33]. Pratt & Whitney engines were included in four of the five pilot aircraft projects. According to NASA, this project aims to "develop an aircraft that will use fuel less by 50%, produce emissions less by 75% and will be less noisy than modern vehicles.

The company advantages are the availability of a working fan drive system through a reduction gear. By gaining experience in operating a new solution, the company will be able to minimize further technical risks associated with this system. The GP7200 engine previously reviewed and the PW4000 and PW2000 engine families that are not to be considered can provide the experience of developing an engine of the required thrust class for Boeing NMA.

AII.3 Time of putting technologies in operation

The possibility of introducing new technical solutions into operation is conveniently assessed on a scale of technological readiness level (TRL) adopted by NASA [34]. There is a dependence on the time of commissioning a new technology on the technological readiness level (TRL). To assess the possible gain in reducing fuel consumption, we also use the data given in [34] and shown in Table 1.

Table 1. Prospective engine technologies and expected commissioning time

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current TRL	Availability of technology (calculated)
	Counter Rotating fan		after 2020	15 to 20%	3	2023
	open Rotor/Unducted fan		after 2020	15 to 20%	5	2019
	New engine core concepts (2nd GeN)		after 2030	25 to 30%	2	2026
	embedded distributed Multi-fan (2nd GeN System)		after 2030	< 1%	2	2026
Advanced engine Concepts	fan	Component Improvements	before 2020	2 to 6%	8	2013
		Zero Hub fan	before 2020	2 to 4%	7	2016
		Very High BPR fan	before 2020	2 to 6%	7	2016
		Variable fan Nozzle	after 2020	1 to 2%	7	2016
	Combustor	Variable flow Splits	after 2020	1 to 2%	5	2020
		Ultra-compact low-emission combustor	after 2020	1 to 2%	5	2020
		Advanced Combustor	before 2020	5 to 10%	8	2013
	Compressor	Bling-concept	after 2030	1 to 3%	3	2023
		Blisk-concept	after 2020	1 to 3%	7	2016
	Variable Geometry Chevron		after 2020	< 1%	5	2020
Nacelles and Installation	Buried engines		after 2020	1 to 3%	5	2020
	Reduced nacelle weight		before 2020	1 to 3%	7	2016
engine Cycles	Adaptive Cycles		after 2030	5 to 15%	2	2030
	Pulse detonation		after 2030	5 to 15%	2	2030

Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Current TRL	Availability of technology (calculated)
	Boundary Layer Ingestion Inlet		after 2020	1 to 3%	3	2023
	Ubiquitous composites (2nd GeN)		after 2020	10 to 15%	3	2023
	Adaptive/Active flow control		after 2020	10 to 20%	2	2026

Thus, being aware of the technological readiness level of any technology, it is possible at any of the stages to estimate the remaining time before commissioning. However, it is also necessary to understand clearly that various factors may affect the expected commissioning period. This may be the high cost of developing a system (a mechanism) or revealing fundamental, contradictory difficulties in creating technology. The stated data for the commissioning time is approximate.

AII.4 Conclusions

In the conclusions, the review of changes in specific fuel consumption by turbofan engines, which power mainline aircraft, is stated. These engines are of the Rb211, CF6, CFM-56, GE90, GEnx, PW4000, Trent families. For these engines in Figure 51 and Figure 52, the values of pressure ratio and bypass ratio are plotted respectively at known specific fuel consumption and at cruise condition. According to these points, approximation dependences of specific fuel consumption are built as for the value of pressure and bypass ratio. Conventionally, the dependence of specific fuel consumption on the degree of pressure ratio can be reviewed as a characteristic of engine perfection as a heat engine. The dependence of specific fuel consumption on bypass ratio can be considered as a characteristic of engine perfection as a propulsion unit.

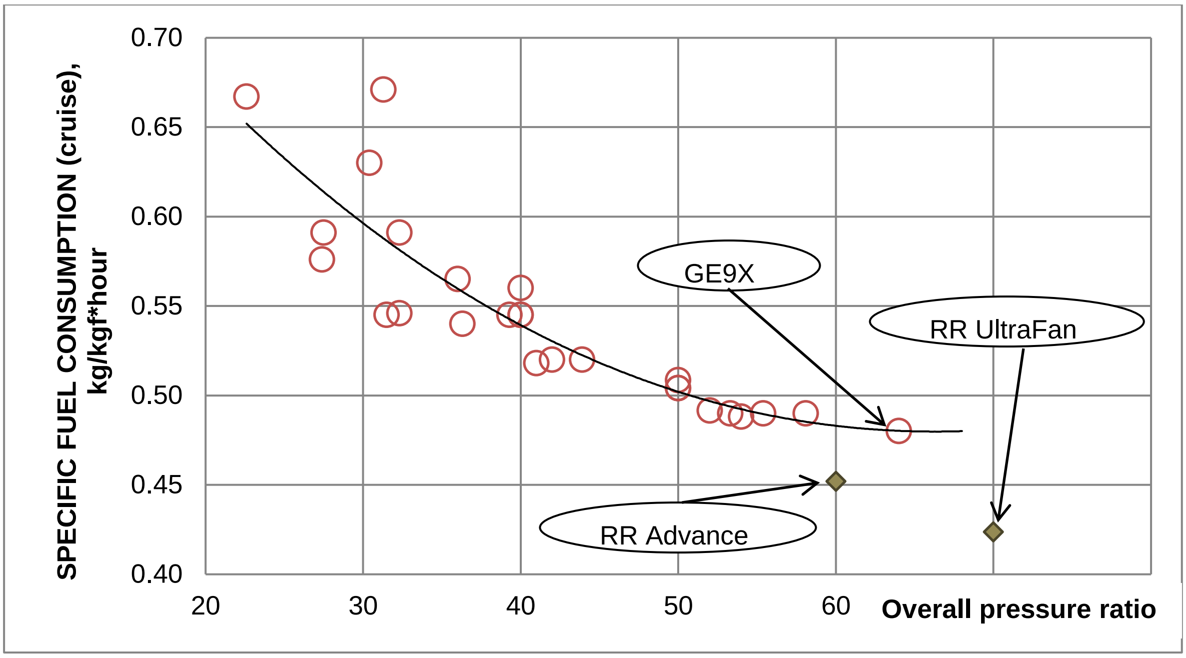


Figure 51. Dependence of specific fuel consumption on the total pressure ratio for engines of long-haul aircraft

The review of the stated dependences makes possible to conclude that modern engines are close to the limit of using the engine as a heat propulsion unit. Increasing the pressure ratio (and, as a consequence, gas temperature at combustion chamber outlet) will not bring a significant improvement in fuel consumption. The expected characteristics of the RR Advance engine are difficult to achieve. This, in turn, will require innovative solutions and additional research to achieve the stated characteristics in terms of the thermodynamic perfection of the engine. Funds spent on further improving the parameters of the thermodynamic cycle can exceed those obtained from the gain in fuel efficiency [6]. Further improvement of engine fuel efficiency as a thermodynamic machine is possible with the introduction of a working cycle with variable parameters, intermediate air cooling, etc.

The efficiency of the turbofan engine as a propulsion unit characterizes the dependence of specific engine consumption on bypass ratio (Figure 52).

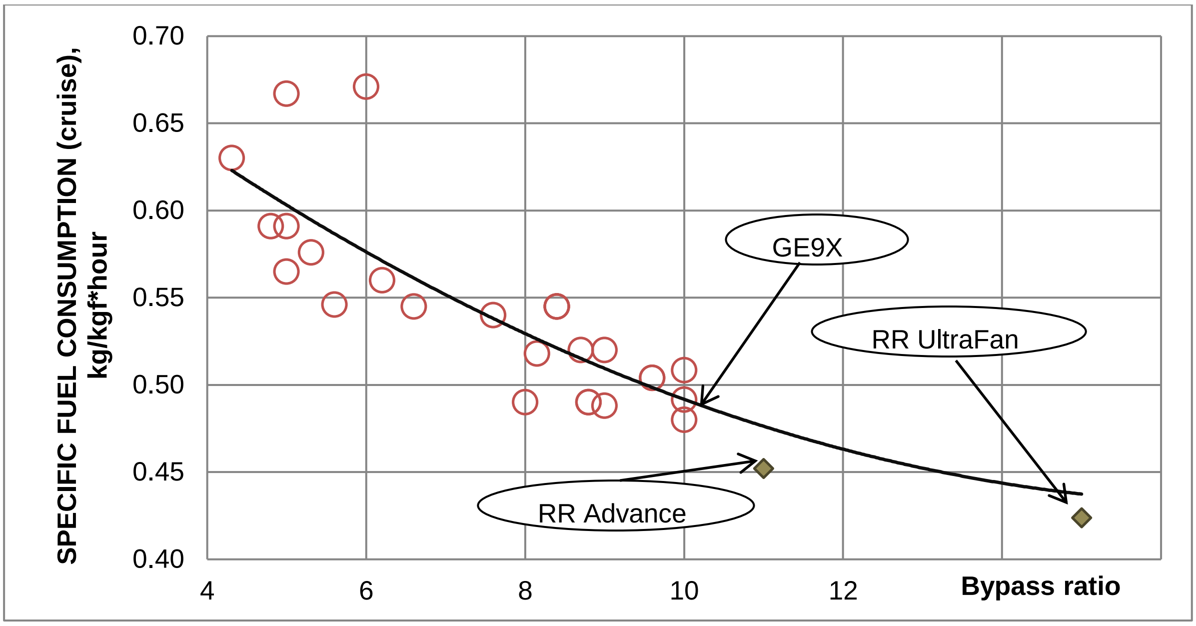


Figure 52. Dependence of specific fuel consumption on bypass ratio for engines of long-haul aircraft

The review of the stated dependence enables us to conclude that a further increase in the fuel efficiency of the engine is possible by raising the bypass ratio. The application of technologies that provide an increase in the bypass ratio will have a greater effect than technologies that improve the perfection of the engine as a heat engine. Thus at this stage of development of aviation engine manufacture, it is expedient to improve the engine as a propulsion unit and proceed to a thermodynamic cycle with controlled parameters. At the same time, it is necessary to consider that as the fan diameter increases, the aerodynamic resistance of the engine will also increase, therefore, it becomes necessary to search for the optimum value of the engine bypass ratio.

Thus, with the progressive development of the engine industry, approaching the theoretical limits that restrict elaboration of modern engine configurations, the emergence of new materials and tools for the design of engine units, a transition will be exercised to new configurations and engine types.

Annex III Assessment of turbofan engine manufacturers

AIII.1 Positions in the market of major turbofan engine manufacturers

"In the entire history of commercial aviation, jet propulsion systems have moved from 20% to 40% of the total efficiency, and there is an understanding in the designers' community that a 60% bar may well be taken.

As usual, as the efficiency of the aircraft — the engine and the airframe — increases, each new step forward becomes more difficult.

Thermodynamic efficiency scales with engine size. Larger engines are more efficient, often because they power larger aircraft, which - in turn - are more efficient. But in order to increase the efficiency of the aircraft with its constant size, you need to reduce the engine. And a reduction of the power plant reduces its efficiency - this is our main challenge now."

Dr Alan Epstein, vice president of technology and environment, Pratt & Whitney, speech at American Institute of Aeronautics and Astronautics Forum in Atlanta [35].

Competition and innovation are in the root of engine designers. In these sections, we provide some hindsight into the current position on the market of the main engine producers. In a snapshot, we can summarise the status of turbofan engines evolution as follows:

- Increase in engine efficiency by 15-20% is quite a realistic objective.
- Pratt & Whitney continues development by using a geared drive. The principle is as follows: the fan is separated from the low-pressure compressor and the turbine with a drive, and in this case, each module runs at optimum speed, but the fan is slower than the low-pressure compressor and the turbine, which run at significantly higher speeds.
- Safran is testing an open rotor.
- GE Aviation is focused on thermodynamic improvements and recalculates the cycles.
- Rolls-Royce also uses a reduction gearbox, in order to reduce the turbine and compressor. This increases the pressure ratio - the target is 60: 1.

Figure 53 and Figure 54 show the market shares of the largest turbofan manufacturers for 2014 and 2017: General Electric (USA), Rolls Royce (United Kingdom), Pratt & Whitney (USA), Snecma (France), Honeywell (USA), Turbomeca (France), Solar Turbines (USA), Motor Sich (Ukraine).

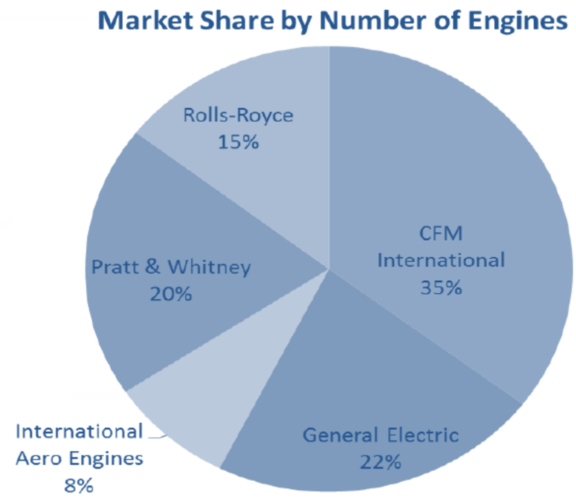


Figure 53. Diagram of turbofan manufacturers positions in the market for 2014[36]

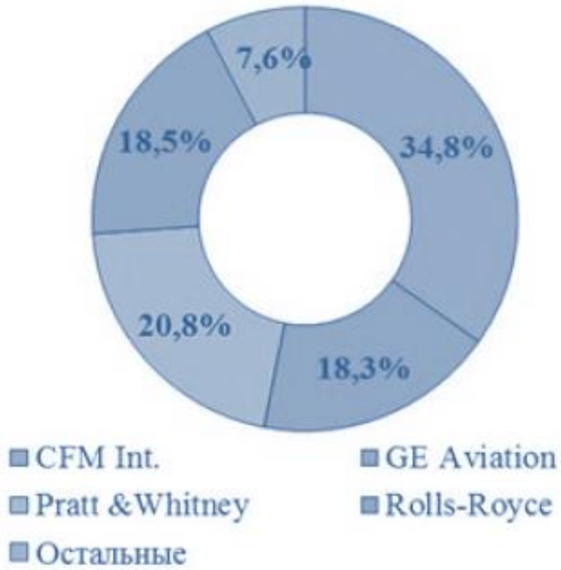


Figure 54. Diagram of turbofan manufacturers positions in the market for 2017[37]

AIII.1.1 Pratt & Whitney

Pratt & Whitney have already implemented their main idea of increasing the power plant efficiency through the development of a geared drive system on the PW1000G engines family. They plan to develop in the same spirit, which will lead to a further reduction in the pressure ratio of a fan. The result: reduced fuel consumption and noise.

The company's second technology is being developed at the NASA research centre in Cleveland, Ohio (Glenn Research Center) under the Continuous Low-Energy, Emissions and Noise (CLEEN) program of the Federal Aviation Administration (FAA). The studies focus on three key factors by 2030 against the level of 2000:

- fuel consumption reduction by 33%,

- carbon dioxide emissions reduction by 60%
- noise reduction by 32 dB.

AIII.1.2 Safran

According to the expectations of the French aircraft engines manufacturer Safran, the efficiency of increasing the engine performance will increase due to the trend of increasing the bypass ratio, as well as increasing the thermodynamic efficiency. This scheme is planned to be implemented until the mid-2020s, the result of which will be another 10-15 percentage points of the overall efficiency.

One option is the concept of propfan, or counter rotating open rotor (CROR). Although the idea is not new, no one has yet been able to bring it to life, but Safran experts are going to overcome it by improving the modelling and using the lightweight, high-strength materials. Today, the company has a CROR prototype with a bypass ratio of about 35, but with a number of unresolved problems. The main of them is the noise level, which is produced by an open fan.

Safran believes that they managed to overcome it, reducing it to current standards, and now they are moving to tests of controls, vibration and methods of its monitoring. If these indicators can be curbed without serious interference in the design, then the resulting engine will have 15% more fuel efficiency compared with today's leaders.

Safran experts claim that they have coped with this problem, and are testing controls now, as well as deal with the problems of vibration and how to monitor it. After solving the problems in using an open rotor, there is a need to change the design of the airframe, which is still to be solved by Safran engineers.

AIII.1.3 GE Aviation

General Electric is developing solutions to simplify the design and improve the thermodynamic part by increasing the pressure in the compressor and the temperature in the turbine while reducing the pressure ratio in the fan.

The company is going to modify not just some part in the design, but the entire cycle and to use adaptive cycles, mainly in engines for military aircraft. General Electric experts are studying the concept of propulsion with increased pressure based on a modified Brighton cycle and burning with a constant volume for power plants of sixth-generation combat vehicles on demand of US Air Force.

Also, the company continues to design rotating and static parts made of ceramic matrix composite (CMC). This composite outperforms the metal in temperature and weight: it is able to withstand higher temperatures than the metal and at the same time, it is almost three times lighter in weight. In addition to the existing production site in Asheville, North Carolina, GE is investing more than $ 200 million in a new facility in Huntsville, Alabama, including $ 21.9 million of research funds from the United States Air Force. It is expected that at these two sites the silicon-carbide fibre matrices will be obtained for mass production of CMC parts in 2018.

Future developments will be used in modern CFM LEAP engines of a joint venture between GE and the French Safran. Namely, as turbine composite shrouds, 18 pieces for each engine. Also, in a new development, GE9X, it is planned to use new material in the combustion chamber, and high-pressure turbine blades (42 pieces). According to estimations, by mid-2020, the demand for composites will increase 10 times, so these are quite timely modifications.

All of the above modifications, namely increasing the temperature in the combustion chamber and, of course, reducing the weight of the power plant due to the use of silicon-carbide parts, will lead to a reduction in fuel consumption by 20%, according to the manufacturer's calculations.

New developments for military aircraft may become a revolutionary solution for passenger aircraft in the future.

AIII.1.4 Rolls-Royce

The Vision 10 technology package for a new UltraFan engine provides for a geared fan, a bypass ratio of 15: 1 and a pressure ratio of 70:1.

Such major changes imply some changes in the architecture of the Trent core, namely, part of the work performed by the intermediate-pressure turbine is transferred to the high-pressure turbine (Figure 55).

Inclusion of the Power Gearbox (PGB) system will drive a large fan with an increased bypass ratio and will allow getting rid of the low-pressure turbine and compressor. The new configuration is called "two-and-a-half-shaft", in which the accessory gearbox is smaller in weight compared to the components to be removed, which is a great addition to the already successful modification.

Figure 55. Rolls-Royce engine evolution [35]

AIII.2 Predictions of positions in the market of major turbofan engine manufacturers for 2030

General Electric Aviation will have a market share of 18.3% by 2030. The company has a wide range of engines both for civil commercial and transport aircraft (GE90, GEnx, GE9X), and for military aircraft and helicopters. The sales of the F110 military engines for Lockheed Martin F-16 fighters, as well as F404 and F414 for Boeing F/A-18, will be stable but may decline if these aircraft begin to be decommissioned. Taking into account the share of the company's participation in the CFM International joint venture, it can be concluded that by 2030 GE Aviation will become a key player in the booming market of turbofan engines.

Rolls-Royce, as a manufacturer of engines for Boeing and Airbus wide-body long-haul aircraft, will have a market share of 18.5% (about $ 211.4 billion) by 2030. The company's production sites are located in the UK, Germany and the USA. Most of the revenue will come from the production of Trent engines in the UK.

Pratt & Whitney will be the second player with a market share of 21%. Most of the sales will be accounted for by commercial engines of the PW1000G family for narrow-body aircraft of the Airbus A320neo product line. Also, a significant share in the Pratt & Whitney's revenue structure for this period will be F135 military engines for the Lockheed Martin F-35 fighter, since the purchases of this aircraft will continue over the next 20 years by both the US Air Force and other allied countries. Gradually decreasing sales of F100 family engines will also bring a small part of the revenue, but its size will depend on the decommissioning rate of the F-15 and F-16 fighters. In case of accumulation with the sales of engines for business aviation and transport aircraft, the company's total revenue for the period under review will amount to more than $ 238 billion, excluding revenue from the sale of spare parts and services.

CFM International will be the leader in the market of turbofan engines in the period 2016-2030 having a market share of 35%. After the highly successful commercial engine CFM56 installed on thousands of narrow-body Boeing and Airbus aircraft, the main part of the profits in the next 15 years will come from the latest LEAP engine, which will be used on a large number of modifications of the Airbus A320neo, Boeing 737 MAX and Chinese COMAC C919 aircraft [37].

AIII.3 DFM international

AIII.3.1 CFM technological and design problems and their impact

AIII.3.1.1 Problems of making new blades for Leap

It would be challenging enough for Precision Castparts (an American company that manufactures casting moulds, forged parts and aerodynamic castings for the aerospace industry) to speed a process known as investment casting. The procedure starts with a wax mould dipped in a ceramic slurry and ends with a turbine blade made from a single metal crystal capable of withstanding enormous forces and temperatures of 2,800 degrees Fahrenheit (1,540 degrees Celsius).

But to handle the Leap's hotter temperatures, GE created a more complex high-pressure turbine blade. While the design is a closely held trade secret, a person familiar with it described a double-wall casting with a special core and advanced inner-wall cooling.

The new engine also has two high-pressure stages, said Michaels, the consultant at AeroDynamic Advisory, which means it has about double the 80 high-pressure turbine blades on an older model, the CFM56. That increases the workload for Precision Castparts and Arconic, which can make things worse. The company has yet to refine the technology and design of the new Leap engine.

For a mature engine, the percentage of blades produced that meet a manufacturer's standards are typically in the 90% range, Michaels said. But the so-called first-time yield can be half that for a new and complex design like the Leap until production techniques are honed.

While the foundries have made progress, their yields can still fluctuate from week to week, and the inconsistency is affecting the smooth flow of parts like turbine blades, one of the people said [38].

AIII.3.1.2 Heat insulation problems in LEAP engines and their consequences

Problems were identified in November 2017. The fault is related to the premature loss of the environmental barrier coating in the high-pressure turbine disks of LEAP-1A and LEAP-1B power plants for narrow-body Airbus A320neo and Boeing 737MAX aircraft, respectively [39].

New-production LEAP engines incorporate the permanent ceramic matrix composite (CMC) fix developed by CFM International. The fix mitigates an environmental barrier coating degradation issue that affected the CMC shroud surrounding the first high-pressure turbine stage.

This fault has never represented a safety issue, but the loss of coating reduces the amount of exhaust gas temperature (EGT) margin available to Leap engines, affecting their performance levels at high thrust settings. This led to operators sending engines prematurely for performance-restoration maintenance shop visits after only a few thousand hours' time on-wing.

The fix relied on the fact that the designs of the two Leap models "had available extra EGT margin" which CFM knew about from testing. So CFM engineers "were able to restore 25 degrees of EGT margin through a service bulletin," which instructed Leap operators to implement a Fadec software upgrade that immediately provided them with some additional time-on-wing flexibility.

According to Gaël Méheust, president and CEO of the CFM joint venture, the additional time-on-wing flexibility has allowed CFM and operators to organize Leap removals and environmental barrier coating replacements without any aircraft on ground emergencies occurring.

With the temporary fix in place, CFM developed a permanent fix for the coating-degradation problem by changing the bonding material it had used to bond the environmental barrier coating to the surface of the CMC shroud segments. (The coating is required because the silicon carbide fibre/silicon carbide matrix CMC parts are adversely affected by water vapour in the exhaust gas flowing from the combustor.) "The fix was introduced in June into the production lines," said Méheust [40].

AIII.3.2 CFM operational problems and their impact

In August 2016, in the south-west over the Gulf of Mexico, the Boeing 737-800 lost the CFM56-7B22 engine cowling during the flight, the pilots made a successful landing.

On 17 April, Southwest pilots made an emergency landing after their Boeing 737-700's left-side CFM56-7B22 powerplant exploded, damaging the aircraft with shrapnel and breaking a window, which killed one passenger. The aircraft had been operating flight 1380 from LaGuardia to Dallas but diverted to Philadelphia.

NTSB investigators already traced the failure to a broken fan blade. They found an "internal" crack in the blade near where the blade meets the engine hub.

According to CFM, CFM56-7 has accumulated 350 million flight hours without any problems.

AIII.3.2.1 Expert opinion on the cause of engine failure

Like in 2016 incident, the 17 April engine explosion may not technically qualify as an "uncontained failure" – a term meaning a blade penetrated the casing around the fan, says former National Transportation Safety Board member John Goglia.

"You can see the containment ring, and it's still on the engine," Goglia says after viewing NTSB photographs of Southwest flight 1380. "Further back… you see the containment ring. It's totally intact."

The blade broke near the hub, according to the NSTB. It apparently flew forward, hitting the forward part of the cowling and causing the cowling to disintegrate into shrapnel that damaged the aircraft, Goglia suspects.

Investigators retrieved parts of the cowling on the ground 120km from Philadelphia, the NTSB said.

Experts studying such failures believe the forward trajectory results from pressure behind the blades, he adds. But the extreme rarity of such failures and complexity of forces involved make testing, understanding and predicting blade failures difficult.

The blades whirl thousands of times per minute, forcing cold outside air into hot aft sections, Goglia notes. And incidents like bird strikes, even those years ago, might theoretically degrade blade strength.

According to him, engine manufacturers use the most technologically advanced materials, but this is not the limit, and more tests on the ground are needed for an accurate forecast in the air [41].

Southwest Airlines have launched an internal system to track all of its engine fan blades by serial number, following the inflight failure of a CFM56 engine in April, chief operating officer Mike Van de Ven tells FlightGlobal at the airline's shareholders meeting in Annapolis.

At the beginning of May, the airline completed inspections on more than 35,000 fan blades - an effort that began in 2016 after a similar accident in August of that year, also involving a cracked fan blade. The carrier accelerated inspections of the remaining fan blades following the 17 April accident.

Chief executive Gary Kelly says there were "zero findings" from the inspections that recently wrapped up, but says the airline removed a couple of dozen blades that showed coating anomalies. These were sent back to CFM for further checks that will be more invasive beyond the airline's ultrasonic inspections, he adds.

Van de Ven says that about 20 to 30 blades were returned to CFM, but stresses that the coating anomalies could be simply due to wear-and-tear.

"What I want to be able to say is that every fan blade with more than 3,000 cycles has been inspected and is in a programme to be inspected every 3,000 cycles," says Van de Ven.

The airline estimates it cancelled about 500 flights as a result of the engine inspections [42].

AIII.3.2.2 Ultrasonic blade inspection and its consequences

On April 20, 2018, CFM International issued Service Bulletin for the operators of CFM 56-7B-series engines powering Boeing 737 Next Generation (737-600/-700/-800/-900/-900ER):

- within the next 20 days CFM requires ultrasonic inspections for fan blades accumulating more than 30,000 cycles;
- by the end of August 2018, carry out inspections of the engine fan blades accumulating 20,000 cycles;
- after the first inspection, the operators of these aircraft are recommended to repeat the inspection every 3,000 cycles - approximately every two years with an average intensity of operation

One cycle includes the engine start, take-off, landing and complete shutdown. This is the standard unit when planning for technical inspections and repairs.

On April 20, 2018, the FAA issued emergency AD (EAD) 2018-09-15 based on the CFM International service bulletin. The EAD required CFM56-7B engine fleet fan blade inspections for engines with 30,000 or greater cycles. The EAD required that within 20 days of issuance that all CFM56-7B engine fan blade configurations to be ultrasonically inspected for cracks per the instructions provided in CFM International SB 72-1033, and, if any crack indications were found, the affected fan blade must be removed from service before further flight. On the same day, EASA also issued EAD 2018-0093E (superseding EASA AD 2018-0071) that required the same ultrasonic fan blade inspections to be performed [43].

The bulletin covers approximately 680 engines with 30,000 cycles (about 150 have already been inspected by their operators after the accident with WN1380flight) and up to 2500 engines that have reached 20,000 cycles.

Inspection is carried out by ultrasonic sounding along the surface of the fan blade (the engine remains on the wing) and takes about four hours per engine. It will be required to almost 60 airlines, to which GE and Safran will send about 500 technical specialists for assistance, whose task will be to advise in conducting the inspections and minimize failures in airline schedules [44].

AIII.3.3 CFM International engines meeting the ICAO standards

AIII.3.3.1 Greenhouse gases

Safran and CFM International are the members of the ICAO's working groups, which are developing a future standard for CO2 emissions to the atmosphere. The companies are actively focusing on meeting the objectives set by ACARE (Advisory Council for Aviation Research and Innovation in Europe), through the Vision 2020 and Flightpath 2050 roadmaps, to reduce CO2 emissions by 50% by 2020 (versus 2000), and 75% by 2050.

New LEAP engine involves the technologies reducing fuel consumption by 15% compared with the current generation. By about 2030, a new generation of high-bypass engines, like the open rotor already being studied by Safran Aircraft Engines, will play a decisive role in gaining a further 15% reduction.

AIII.3.3.2 Oxides of nitrogen (NOx)

Oxides of nitrogen (NOx) are regulated by standards issued by the ICAO, as well as local regulations at certain airports. When engines are certified, the level of emissions is also validated. Safran Aircraft Engines and CFM International partner were the first to offer, as early as 1995, a low-NOx combustor, on the CFM56 engine. The upcoming LEAP engines will drastically reduce NOx emissions thanks to the use of a lean-combustion, multipoint injection system, providing a full 50% margin in relation to CAEP/6 standards.

AIII.3.3.3 Hydrocarbon and carbon monoxide emissions

Hydrocarbon and carbon monoxide emissions are also regulated by ICAO standards for engine certification. Safran favours the use of lean combustion technologies, which, in addition to reducing NOx emissions, also decrease the particles released by the engine.

AIII.3.3.4 Acoustics

The considerable technological progress achieved by aircraft and engine manufacturers in the last 40 years has reduced aircraft noise by 75%. Noise is regulated by the ICAO's international standards for aircraft certification.

Safran Aircraft Engines invests heavily in research to reduce noise, aiming for the ambitious objectives defined by ACARE for 2020 and 2050. Safran has coordinated major European research programs, including the recently completed OPENAIR, which nearly reached the targeted 2.5 dB noise reduction, in addition to the 5dB reduction already achieved by the previous SILENCE(R) program. A total of 15 new technologies were validated, concerning both engines and aircraft [45].

The LEAP offers airlines a 15% reduction in fuel consumption and CO_2 emissions (compared with previous-generation engines), along with a 50% decrease in NOx (oxides of nitrogen) emissions, while also meeting the most stringent noise standards (Figure 56). Offering outstanding technical, economic and environmental performance, the LEAP engine has recorded the fastest order rate in the history of commercial aviation. It has logged over 12,230 orders and commitments worldwide to date [46].

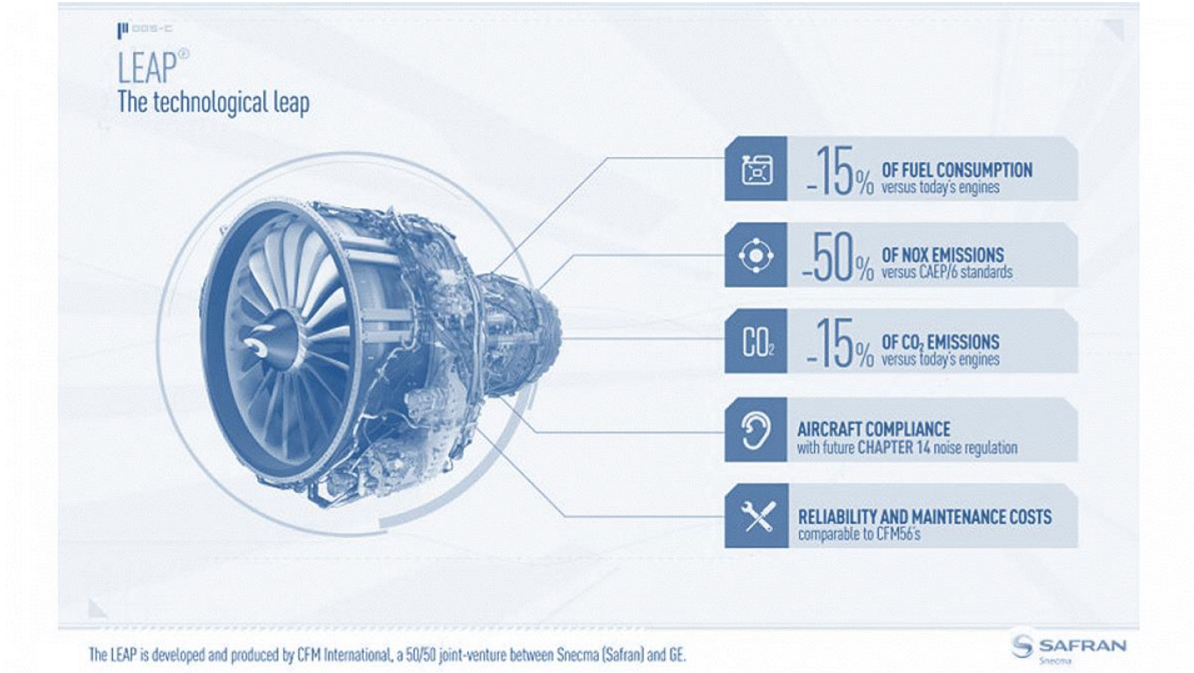


Figure 56. LEAP engine performance [47]

AIII.4 Rolls-Royce

AIII.4.1 Rolls-Royce technological and design problems and their impact

The main problem is the lack of manufacturing fan blades from titanium as they are 20% heavier than their modern counterparts. Also, the various layers of the alloy, can delaminate and crack during operation, which can lead to irreversible consequences [36].

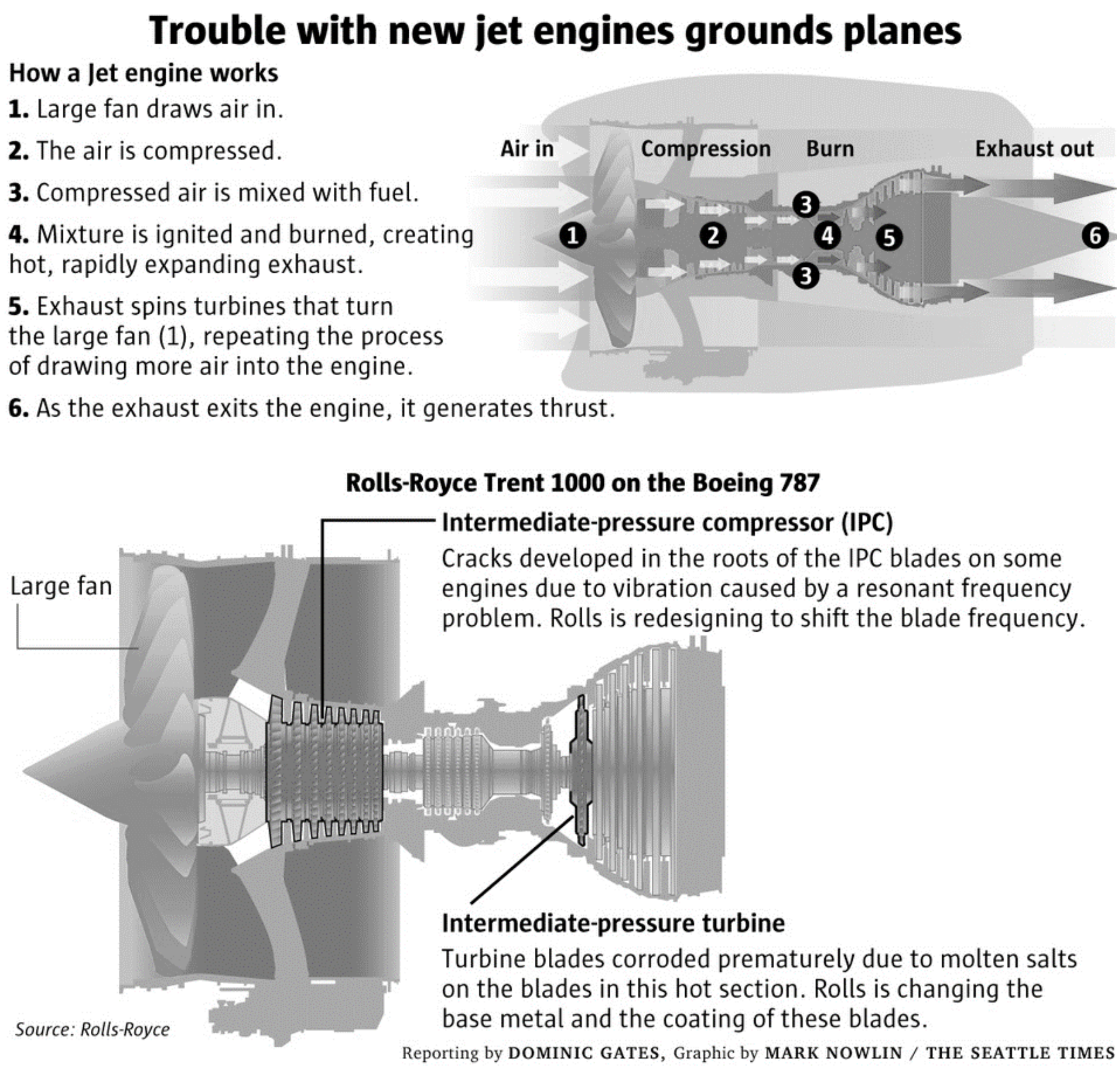


Figure 57. Current problems with Trent-1000 engine [48]

AIII.4.2 Rolls-Royce operational problems and their impact

Thai Airways International has grounded part of its Boeing 787-8 fleet owing to turbine replacement issues with the Rolls-Royce Trent 1000 engine and shortage of spare parts for it.

In September 2016, R-R said it would replace turbine blades in the intermediate-pressure turbine of the global Trent 1000 fleet. The engine-maker said that the existing design was "failing to meet its expected lifespan", and that it would roll out a global fix.

Flight Fleets Analyzer shows that there are 213 in-service 787s globally that are powered with Trent 1000s. Of these, 101 are with operators in the Asia-Pacific.

Globally, major users of Trent 1000 powered 787s include All Nippon Airways with 59 aircraft, British Airways (24), and LATAM (23)[49].

New Zealand investigators have confirmed that two engine failures on Air New Zealand Boeing 787-9s in December 2017 were caused by known issues with the Rolls-Royce Trent 1000s intermediate pressure turbine (IPT) blades.

The Transport Accident Investigation Commission's interim report on the two failures, which occurred on ZK-NZE on 5 December, and ZK-NZF on 6 December, shows that both aircraft were fitted with 'Package C' Trent 1000 engines that failed after take-off from Auckland, forcing the aircraft to return.

Examination of the engines found that they suffered major damage due to the separation of IPT blades, caused by corrosion fatigue cracking [50].

The Australian Transport Safety Bureau is investigating another Trent-1000 engine failure involving a Scoot Boeing 787-9 that occurred on October 11, 2018.

The aircraft was descending into Perth during a flight from Singapore when there was "an uncommanded in-flight shutdown of the right engine." The crew continued the descent and landed safely at 19:21 local time.

Scoot tells FlightGlobal that a component related to the engine was replaced, and it returned to service on 13 October. It adds that the problem encountered by the aircraft "is not related to any known issues regarding the Rolls-Rolls Trent 1000 engine."

The ATSB is planning to complete its investigation during the first quarter of 2019 [51].

AIII.4.2.1 EASA proposes Trent 1000 IP compressor blade checks

EASA has proposed interim measures to address possible blade cracks in the intermediate pressure compressor on Rolls-Royce Trent 1000s, while the manufacturer is developing a modification.

The European Aviation Safety Agency states that cracking has been discovered in Trent 1000s with the Pack C performance enhancement measures. These cracks affected blade in the intermediate pressure compressor's first- and second-stage rotors. EASA says the situation could lead to the release of blades during flight.

Rolls-Royce has issued a service bulletin instructing inspections of the compressor's rotor sections, and EASA is proposing to mandate these examinations [52].

AIII.4.2.2 Boeing's opinion on Trent-1000 problems

Boeing officials say they are working with Rolls-Royce on pervasive durability problems with a large subset of the Trent 1000 fleet that has grounded multiple 787-9s for long periods.

Concerns about the durability of the blades in the Trent 1000 Package C's intermediate pressure turbine and intermediate pressure compressor extend well beyond the well-publicised flight disruptions suffered by Air New Zealand, says Boeing 787 chief engineer Bob Whittington.

"All of the Rolls-Royce operators across the fleet have seen some of the wear-out issues in the Rolls-Royce engine," Whittington says.

R-R is designing a new IPC blade for Trent 1000 engines in the Package C configuration. The IPC blades have come under scrutiny since mid-2018 after an engine failure on board a Scoot 787-9. Singapore's Transport Safety Investigation Agency found that two other shutdowns on Scoot 787-9s were linked to IPC failures probably caused by material fatigue.

Since 2016, R-R also has been replacing the blades in the IPT module of the Trent 1000 after All Nippon Airways reported a series of engine failures. R-R traced the cause of that problem back to suphidation corrosion cracking [53].

AIII.4.2.3 What do Trent troubles mean for Rolls-Royce?

In 2016, Rolls-Royce first announced a durability issue with blades in the Trent 1000's intermediate-pressure turbine (IPT).

Airlines had to park Dreamliners as engines required unscheduled maintenance to replace IPT blades, and aircraft could not be returned to service amid a shortage of available spare Trent 1000s – some carriers had to lease additional capacity. Meanwhile, it became clear that on certain Trent 1000s the durability issues also extended to the high-pressure turbine (HPT) and intermediate-pressure compressor (IPC).

The costs are already mounting: R-R disclosed in March that in 2017 it incurred a charge of £227 million ($311 million) related to addressing technical issues on Trent 1000s and the Trent 900s powering Airbus A380s. And the UK engine maker said that this year, the upgrade programme's annual cash impact would "broadly double" from last year's £170 million, before dipping in 2019 as work drops off.

However, that was before the revelation in April of "additional disruption" – and higher costs – from further inspections required to address IPC blade durability issues on Trent 1000 Package C engines.

AIII.4.2.4 Engineering resources

Teal Group vice-president analysis Richard Aboulafia wonders whether R-R's issues with the Trent 1000 – and Pratt & Whitney's problems with its PW1000G geared turbofan – might be a result of having "greater ambitions than resources".

The technical challenges and required engineering effort to develop more efficient engines have hugely increased from previous generations of equipment. More broadly, Aboulafia thinks the Trent 1000 problems show that "we are on the very limits of squeezing performance improvement out of existing turbine architectures" and that highly engineered parts come with a "certain set of vulnerabilities".

Especially on Airbus and Boeing's latest aircraft programmes – the A320neo, A330neo, 737 Max and 777X – fuel-efficiency gains have been mainly, if not entirely, achieved through new engine technology. As a result, the airframers have redistributed much of the research and development effort, and therefore risk, for new programmes to the engine manufacturers; at the same time, Airbus and Boeing have put engine suppliers under pricing pressure and driven production to record levels.

"The ability to add resources at the engine companies was constrained at exactly the moment when so much was expected of them," Aboulafia says.

Boeing 787 chief engineer Bob Whittington revealed in January that "all" operators of Trent 1000-powered Dreamliners were affected by "some of the wear-out issues in the Rolls-Royce engine", which entered service in 2011.

The initial IPT blade replacement programme for the Trent 1000 was disclosed after All Nippon Airways (ANA) had temporarily grounded some of its 787s in 2016 because of premature, corrosion-related part failures.

R-R redesigned the IPT blade and introduced it on the latest version of the Trent 1000, the 1000 TEN, and on the Trent 7000 derivative that powers the Airbus A330neo. The new part is being retrofitted to earlier Trent 1000s and, says R-R, should resolve the durability issue. But the modification programme nevertheless caused a wave of shop visits as some engines required urgent blade replacement.

AIII.4.2.5 Operational disruption

There has been an inevitable disruption for operators: Air New Zealand (ANZ) temporarily grounded several Dreamliners after experiencing in-flight failures on two of its 787-9s in December 2017. The carrier resorted to wet-leasing aircraft to support its schedule.

Virgin Atlantic in January disclosed plans to add four A330s to its fleet and return to service a stored A340-600 in a bid to improve "resilience" of its operation "in light of an industry-wide shortage of Trent 1000 engines".

The IPC blade issue was first disclosed after an engine failure aboard a Scoot 787-9 in late 2016. Singapore's Transport Safety Investigation Bureau determined that the failure was caused by an IPC blade that had broken off – probably as a result of material fatigue – and linked two further shutdown events on Scoot 787-9s last year to the same issue.

R-R says the cracking problem applies to Trent 1000 with Package C configuration and that neither the TEN nor the Package B version is affected. The manufacturer is in the process of preparing redesigned blades for the IPC – and for the HPT where erosion is an issue on existing blades.

The new parts are scheduled to become available by year-end and will be retrofitted to affected engines. R-R believes that the modification effort can be completed during planned, rather than unscheduled shop visits.

R-R says Trent 1000 TEN compressors "are of different designs to the Package C", and that "a new standard" HPT blade is installed on the TEN.

AIII.4.2.6 ETOPS limitations

Following the April disclosure relating to the IPC, the European Aviation Safety Agency mandated that operators conduct repetitive on-wing borescope inspections for all Package C engines and introduced additional inspections for powerplants employed for extended twin-engine operations (ETOPS).

Meanwhile, the US Federal Aviation Administration more than halved the time that Trent 1000 Package C-powered 787s can fly under ETOPS regulations, to 140min, from a previous maximum of 330min.

The US regulator says that if an engine were to fail and the remaining powerplant already had cracked IPC blades, the "likelihood of the remaining engine failing will further increase before a diversion can be safely completed".

Bloomberg Intelligence warns that the ETOPS restriction could put R-R at a disadvantage on the 787 versus rival GE Aviation and its GEnx engine.

Bloomberg senior aerospace analyst George Ferguson asserts that airlines will be required to "adjust operations to remain closer to diversion airports", and that this "reduces efficiency and range, especially for extreme long-haul operations, which are most appealing for 787 buyers". He describes the FAA directive as a "blow" to R-R and operators of Trent 1000 Package-C-powered 787s, which will "probably hurt sales and value for the airplane".

ANZ subsequently disclosed that it needed to introduce refuelling stops on certain 787 flights as new weight restrictions apply to aircraft with affected engines. ANA and British Airways, meanwhile, say the ETOPS changes have had a minor effect on their operations.

R-R's effort to resolve the Trent 1000 problems and modify the in-service fleet "takes an awful lot of resources", which will likely have an impact on the company's ability to concentrate engineering staff on other projects like future engine development, Aboulafia suggests.

He says the development and implementation of modifications for issues on in-service engines is "fairly labour-intensive stuff", while the ramping-up of production for new engine programmes, such as the Trent XWB for the A350, is largely a matter of capital expenditure.

R-R says it had to redeploy "engineering resource" to tackle the Trent 1000 issues, but notes: "[We] expect this to be a temporary measure." The manufacturer says its developmental Advance and UltraFan engine programmes "continue to progress as expected".

AIII.4.2.7 Long-term repercussions

Aboulafia does not believe that airlines and aircraft manufacturers have lost faith in R-R as a result of the Trent 1000 woes. Operators which have ordered Trent 1000-powered 787s have not yet switched to the GEnx. But he warns that the problems have not done R-R "any favours" either and that "a lot of it depends on how quickly they can make it good".

R-R foresees that solutions for the existing issues will be implemented throughout the fleet by 2022.

However, Aboulafia suggests the Trent 1000 problems could have an effect on future orders: "I think where it might hurt is where people are looking at A350-1000 XWB versus 777X and... A330neo versus 787." Both of the Airbus programmes are exclusively powered by R-R engines.

"The big issue here for Rolls-Royce is that the 787 is their only connection with Boeing right now," says Aboulafia.

GE, Pratt & Whitney and R-R have all submitted engine proposals for Boeing's projected New Mid-market Airplane (NMA), which could enter service around 2025. If Boeing were to launch the NMA programme without R-R on board, it would leave the UK manufacturer having almost the entirety of large engine business – all in-production models except the Trent 1000 – tied to Airbus.

That is already the case today, as the Trent 700, 900, 7000 and XWB are exclusively employed on Airbus long-haul aircraft. But Aboulafia thinks a further re-enforcement of that alliance in the long-haul segment is a "very risky concept" for R-R.

GE is, likewise, the sole engine supplier to Boeing's 777 and 747-8 programmes. But the US engine maker also has, via its CFM International joint venture with Safran, a strong position in the high-volume narrowbody market. Since it withdrew from the International Aero Engines consortium with P&W, Japanese Aero Engines and MTU, R-R has no active participation in the single-aisle segment [54].

AIII.4.3 Rolls-Royce engines meeting ACARE standards

Rolls-Royce is a key partner in ACARE (Advisory Council for Aeronautics Research and Innovation in Europe). ACARE's vision for the future, Flightpath 2050, lays out clear environmental technology goals for aircraft relative to the year 2000 benchmark. Achieving these will take contributions from aircraft and engine technology, as well as improvements in airline operations and air traffic management.

ACARE goals together with Rolls-Royce are the following (Figure 58):

- Cut CO_2 emissions by 75%;
- Cut NOx emissions by 90%;
- Reduce noise pollution by 65%.

In order to cut CO_2 emissions by 75%, it is required to reduce the engine fuel burn. Achieving a 75% reduction in fuel burn is equivalent to cutting 275 miles per USG or 1Litre per 100km, per passenger

Rolls-Royce invests in low emissions technology to meet the Flightpath 2050 targets.

Flightpath 2050 also calls for a perceived noise reduction of 65% by 2050. Noise reduction of a large twin-engine aircraft by 15dB is equivalent to Learjet 45 which weighs 25x less and has 20x less thrust[55].

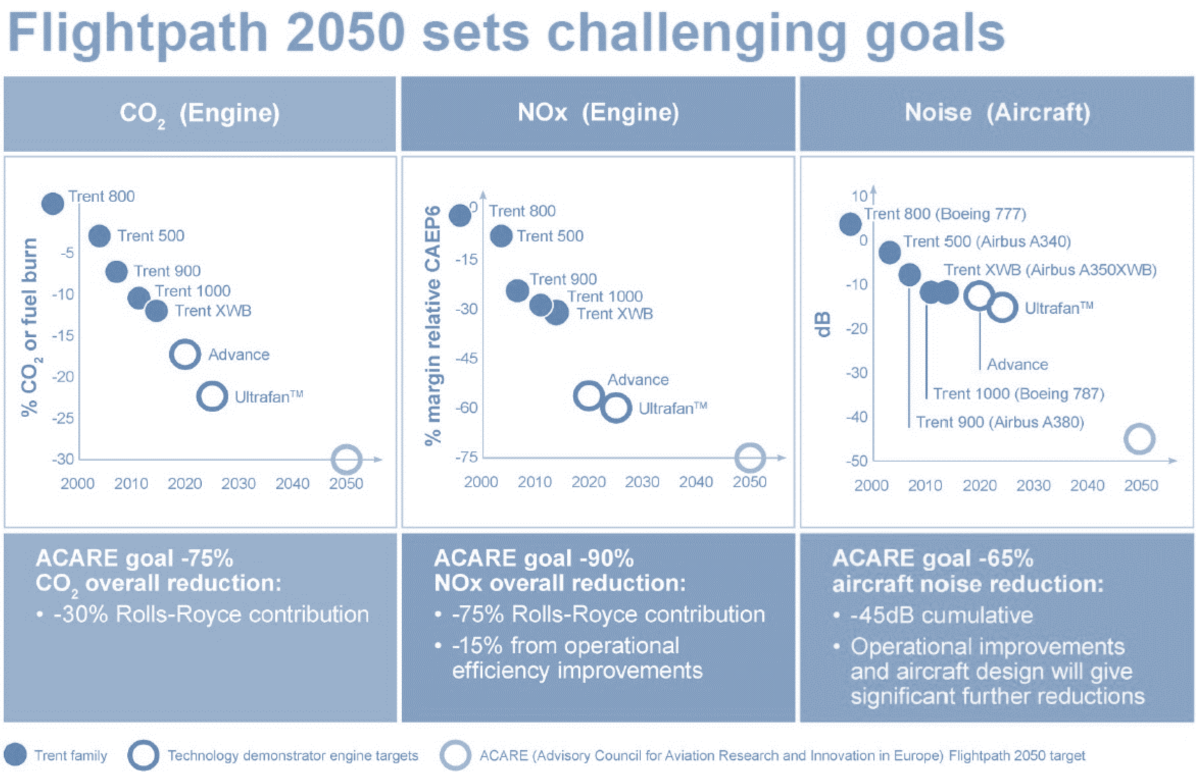


Figure 58. Flightpath 2050 goals [56]

AIII.5 Pratt & Whitney

AIII.5.1 Pratt & Whitney technological and design problems and their impact

One of the most critical deficiencies was P&W's hybrid metallic fan blades, composed of titanium leading edges and hollow aluminium bodies. P&W's sole fan blade plant could not produce them fast enough. As the GTF entered the production ramp-up, workers were still learning how to manufacture the exotic items. In 2016, one out of every two blades had to be scrapped because of defects.

Since April, two more facilities have opened in Michigan and Japan to build the blades, adding quantity to the improving quality of the production system.

The mid-turbine frame is one of the most important structural elements in any engine. The part is made using a casting process. As the metallic structure is formed, great care must be taken to eliminate voids at the molecular level. Too many voids, or porosity, causes the entire part to be scrapped. The problem solved by changing the tooling in production and altering the heat treating process in post-production [57].

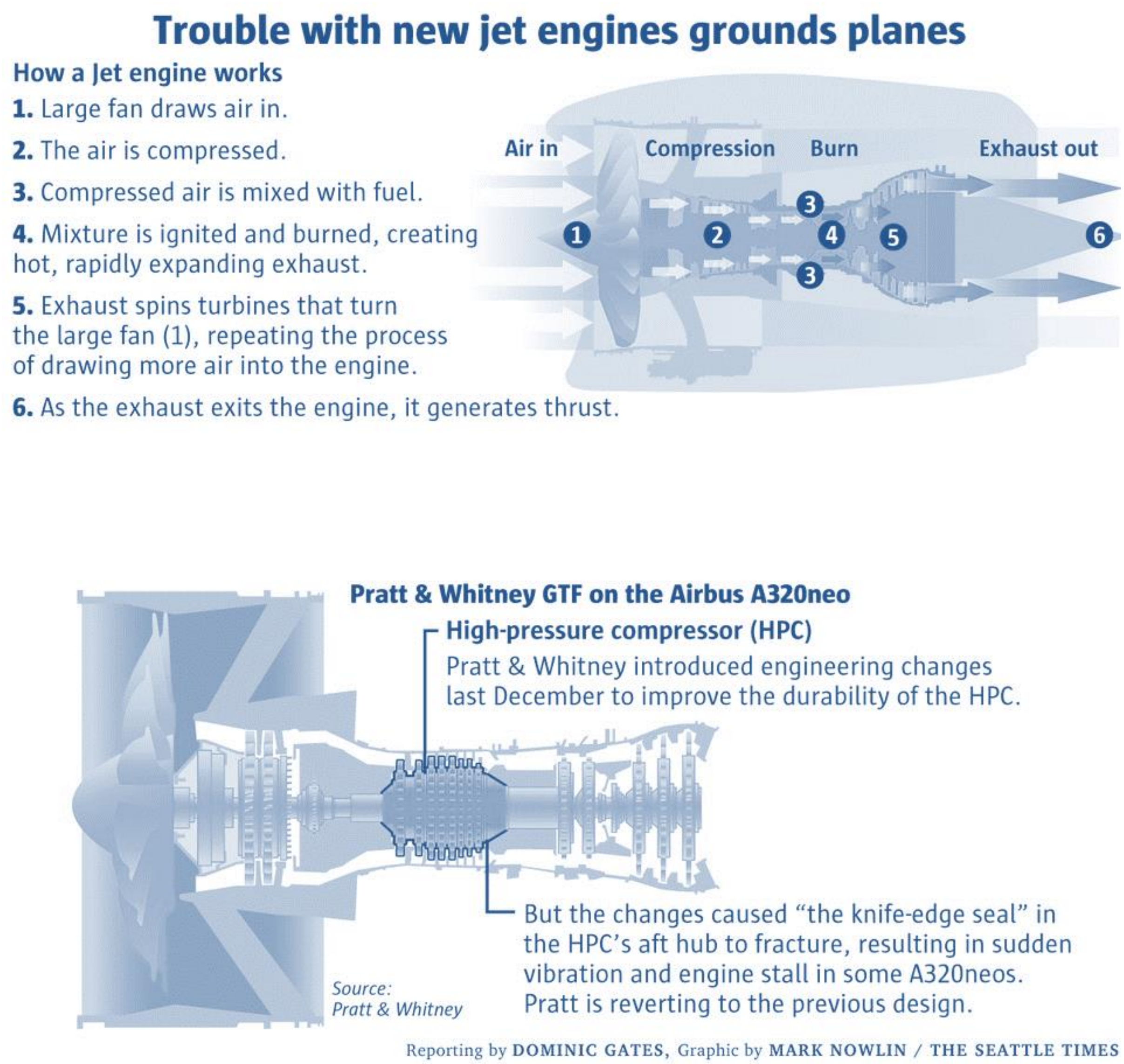


Figure 59. Current problems with Geared Turbofan (GTF) engine[48]

AIII.5.2 Pratt & Whitney operational problems and their impact

After the first 18 months of commercial operations with the PW1100G engine, the main problems with the Pratt & Whitney Geared Turbofan are the following: bowed rotors, parts shortages, prematurely deteriorating components and one in-flight shutdown.

The GTF entered service in January 2016 with several defects that would require almost two years to resolve. The most glaring issue that emerged after entry into service for the PW1100G was a rotor bow problem. All large turbofan engines are affected to some degree by the effect of differential heating on the rotor shaft.

The phenomenon requires airlines to motor the fan on each engine for about 1min to cool off the heated section of the shaft. The PW1100G, however, initially required crews to cool the engines for several minutes each. P&W solved that problem across the fleet by October 2016 by strengthening the shaft bearings, making them less susceptible to the thermal bowing effect.

As that issue was fixed, P&W released details of two more defects in the engine design. Two major parts – combustor liners and carbon air seal assemblies in the No. 3 bearing – proved to degrade prematurely.

P&W rolled out an improved combustor liner design in 2016, but it was not enough to fix the problem. A third-generation combustor liner – internally dubbed the Block C design – is now scheduled to be rolled out in the fourth quarter. The new version tweaks the layout of the internal cooling passages embedded into the combustor liner.

P&W has proceeded with key certification tests, such as extended twin-engine operations (ETOPS), with the existing combustor configuration. ETOPS is a critical certification for Hawaiian Airlines, which has already delayed entry into service of its PW1100G-powered A321neos until 2018.

On the 8th February, GoAir A320neo landed on one engine resulting in immediate, fleetwide inspections of the main accessory gearbox on the PW1100G.

The company spent more than two decades and $10 billion to invent the fan drive gear system, a reduction gear that decouples the rotation speed of the fan and the low-pressure turbine, allowing both systems to rotate at the most efficient speed.

To date, the fan drive gear system has performed exactly as P&W promised. By all accounts, the engine is meeting or slightly exceeding targets for fuel burn production. Notwithstanding the durability issues, the engine's measured dispatch reliability has also met P&W's promised rates, P&W president Bob Leduc tells FlightGlobal [57].

Despite those achievements, CFM International continues to enjoy a slight advantage in market share among announced engine selections for the A320neo family.

In 2018, Pratt & Whitney lost four geared turbofan engines to in-flight failures as a result of a botched durability upgrade.

The engine had delivered on its promised fuel-burn performance after the two-year anniversary of the entry into service of the PW1100G on the Airbus A320neo, and now it was time to move past the supply-chain breakdowns and design glitches that had plagued the pace of deliveries to Airbus and Bombardier CSeries customers.

However, the production halted for a month as P&W replaced a defective knife-edge seal installed in the aft hub of the high-pressure compressor with serial numbers P770450 through P770614. Instead of moving forward, it was replacing a part that had been installed as an upgrade.

P&W's rival for A320neo orders, CFM International, is still months behind on planned deliveries of Leap engines because of a lack of forgings and castings. Rolls-Royce seems in even worse shape, with approaching 50 Boeing 787s parked awaiting a promised fix for a growing pool of defective compressors in Trent 1000 engines.

The engine manufacturers are facing new pressure from Boeing on pricing and aftermarket sales, while GE Aviation and R-R, in particular, and are dealing with corporate-level financial difficulties.

P&W is preparing a raft of new performance and durability upgrades. Opportunities for new applications of the geared turbofan architecture are being submitted. However, the focus now remains on addressing the stockpile of durability problems that have accumulated over the last three years, and the company has taken stock of its situation.

CFM's Leap-1A has a growing lead over the PW1100G, but about one-third of Airbus's customers in the backlog have yet to decide between the two propulsion options. Meanwhile, P&W's supply chain is committed to delivering more than 2,500 engines over the next three years. The company delivered a total of 512 PW1000G-series geared turbofan engines in 2016 and 2017 combined. Beyond the family's five existing customers, P&W is also hoping to attract new applications but has dropped consideration of switching to a different reduction-gear configuration for larger engines.

A special focus will be on the return-to-flight of several PW1100G-powered A320neos in India. Two of the initial A320neo operators, Go Air and IndiGo, have been hit especially hard by the PW1100G problems, with Indian regulators taking a hard stance on precautionary groundings[58].

AIII.5.3 Pratt & Whitney engines meeting ICAO standards and FAR requirements

Pratt & Whitney has developed a new low-emissions combustion system, or E-Kit, that is FAR 25-certified to ensure the JT8D-200 engine stays current with environmental regulations. The E-Kit reduces JT8D-200 engine NOx emissions by 25% and exceeds all ICAO standards for new production engines [59].

In 2007, UTC embarked on a four-year program to reduce greenhouse gas emissions by 12%, water consumption by 10%, air emissions by 20% and non-recyclable waste by 30% compared with 2006.

AIII.5.3.1 TALON COMBUSTION CHAMBER

In partnership with NASA, Pratt & Whitney developed the TALON family of combustors that reduce nitrogen oxides (NOx), unburned hydrocarbons (UHC) and carbon monoxide (CO).

Pratt & Whitney certified the TALON II combustor for use on the PW4158 and PW4168 engines that power the Airbus A300 and A330 aircraft respectively. The TALON II combustor is also in revenue service on the PW6000-powered Airbus A318 aircraft. Here are the results of this upgrade:

- NOx emissions reduction by 19–28%;
- UHC emissions reduction by28%;

- CO_2 emissions reduction approx. by 6% compared to the initial production combustion chambers.

An emissions upgrade kit comprised of improved fuel nozzles and low NOx combustors employing the TALON concept has also been used for the JT8D-200 kit upgrade. The JT8D-200 with the emissions kit is among the cleanest engine in terms of absolute LTO NOx and Unburned Hydrocarbon (UHC) emissions in service today. The emissions kit reduces NOx by over 25%, UHC to virtually zero, and smoke by over 50%. The JT8D-200 QuietEagle™ noise reduction system for MD-80 aircraft was certified in 2006. The QuietEagle meets the following requirements:

- all the requirements of Federal Aviation Regulation (FAR) Part 36 Stage 4,
- International Civil Aviation Organization's (ICAO) Annex 16 Chapter 4 noise standards. It reduces noise by up to six decibels

Additionally, Pratt & Whitney has developed several engine upgrades that enhance the environmental performance of engines including the PW4170 Advantage70™ for the A330 and the V2500-A5 for the A320 aircraft in collaboration with International Aero Engines (IAE) joint venture partners.

The combustor in use is the 3rd generation of technology for advanced low NOx combustors (TALON-X), which was developed with P&W's original design concept of "rich-burn, quick-quench, lean-burn (RQL)." As the emission characteristics, PW1200G provides a margin of more than 50% to the ICAO CAEP/6 standards (Figure 60). The new engine also implemented improved efficiency and noise reduction (Figure 61) [60].

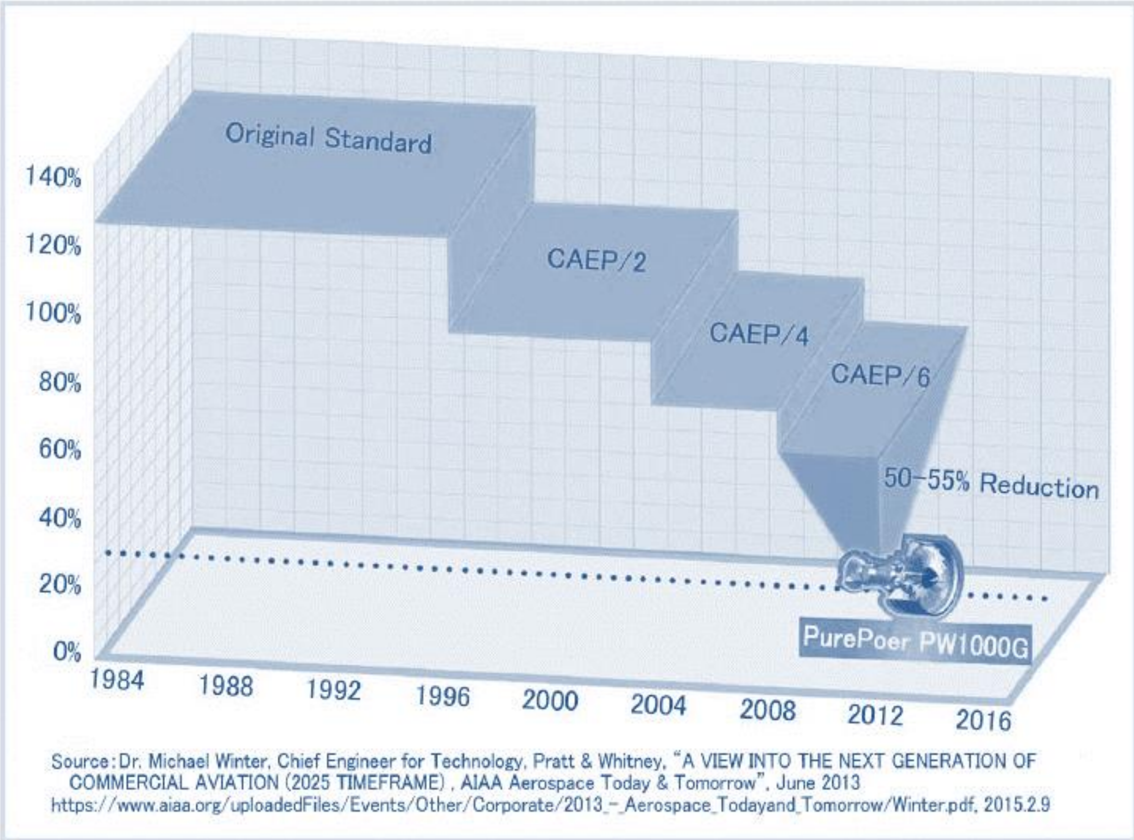


Figure 60. Emission performance

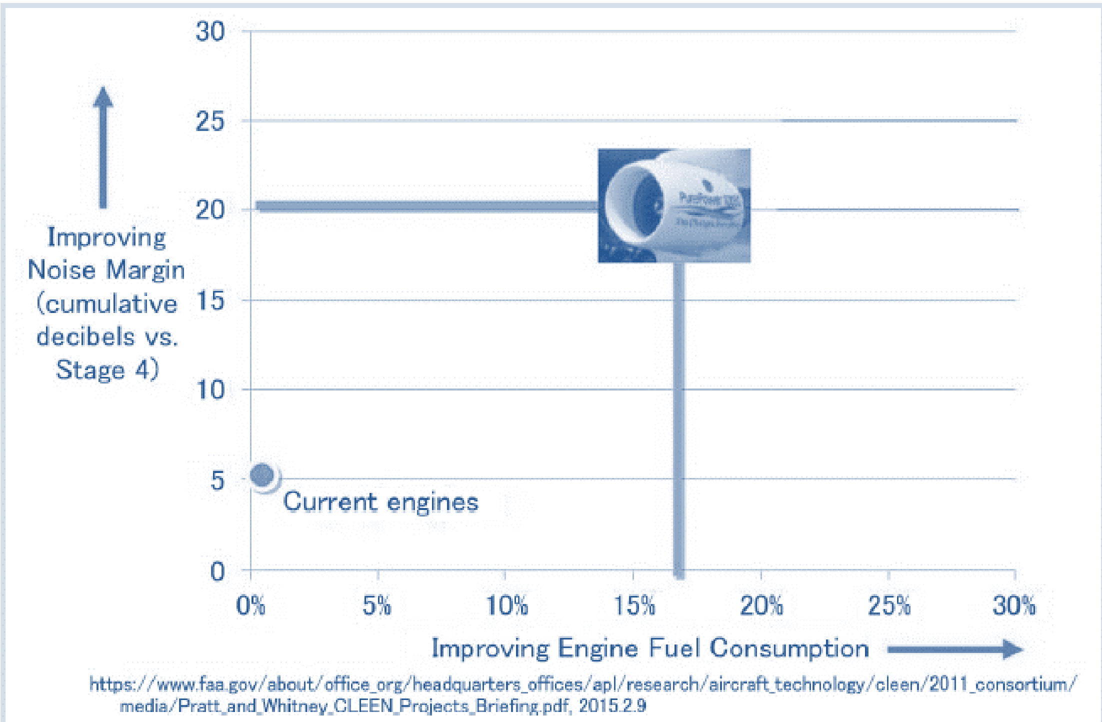


Figure 61. Fuel economy and noise performance

AIII.5.3.2 SYNTHETIC & BIOFUELS

Pratt & Whitney has been committed to exploring the potential of synthetic jet fuels for more than 16 years and is a key partner of the U.S. Department of Defense and Air Force in pursuing clean, energy-efficient solutions that support U.S. energy independence. We also participate in several international working groups to bring alternative fuels into field use.

In early 2008, the Geared Turbofan demonstrator engine successfully operated using an alternative fuel blend during Phase I ground testing in West Palm Beach, Fla. In 2009, a Pratt & Whitney engine was on the first Japan Airlines test demonstration flight that used biofuel.

An Air China Boeing 747 aircraft, powered by Pratt & Whitney PW4000 94-inch engines, completed a flight using a sustainable biofuel in October 2011. No modifications to the aircraft or engine were required for the biofuel, which is a “drop-in” replacement for petroleum-based fuel. The flight was completed as part of the Energy Cooperation Program’s Sustainable Biofuel Program, led by Boeing and other industry members, including Honeywell and Pratt & Whitney.

AIII.5.3.3 ECOPOWER® ENGINE WATER WASH SYSTEM

The EcoPower® engine water wash system reduces fuel burn by up to 1.2% and increases engine exhaust gas temperature margin up to 15 degrees Celsius. Engines washed twice per year lower a wide-body aircraft's average CO_2 emissions by as much as 750 metric tons annually [61].

AIII.6Conclusions

CFM International continues to enjoy a slight advantage in market share among announced engine selections for the A320neo family. But P&W's rival for A320neo orders, CFM International, is still months behind on planned deliveries of Leap engines because of a lack of forgings and castings. Rolls-Royce seems in even worse shape, with approaching 50 Boeing 787s parked awaiting a promised fix for a growing pool of defective compressors in Trent 1000 engines.

Flight Fleets Analyzer indicates that CFM International has an order backlog of around 14,000 Leap engines, variously destined to power Airbus A320neo-family, Boeing 737 Max and Comac 919 jets; there are meanwhile more than 700 CFM56 engines still on order for 737NG and A320ceo-family jets. Given a current production rate of around 2,000 engines a year, the CFM backlog translates to seven years of production.

Pratt & Whitney seems to be in an especially privileged position in the regional jet segment as its PW1000G-series geared turbofan is the sole powerplant available for the A220, Embraer E-Jet E2-family and developmental Mitsubishi MRJ. An engine is also an option on the Irkut MC-21. However, the bulk of GTF orders are for the PW1100G, which powers the A320neo.

The GTF engine has been selected for around 26% of the A320neo's order backlog. For the entire PW1000G series, Flight Fleets Analyzer lists a backlog of around 4,800 engines.

GE has a backlog of around 2,700 engines – spanning the GE90, in-development GE9X, GEnx, CF6 and CF34 types – while Rolls-Royce has a Trent backlog of around 2,400, Flight Fleets Analyzer shows.

R-R says it intends to deliver around 600 Trent engines in 2018 – up from 483 last year – under a plan to ultimately double engine output. GE foresees a roughly 15% year-on-year rise in total deliveries in 2018, to about 4,000 engines, including those produced by CFM and for military customers.

AIII.6.1 Unsolved problems and their consequences

P&W and R-R have received broad coverage for in-service issues on their respective PW1100G and Trent 1000 engines – the latter is an option on the 787 – which have caused disruption for airlines and airframers.

An eight-week delivery suspension of PW1100G-powered A320neos – lasting until April, and related to a flawed knife-edge seal in the high-pressure compressor – was the latest in a series of events that led to more than 100 newly assembled narrow bodies being parked at Airbus production lines at the beginning of 2018 for lack of available engines. Boeing also was forced to store incomplete aircraft because of component shortages, especially of engines.

Leap deliveries had fallen four to five weeks behind schedule owing to supply chain bottlenecks. As part of a recovery plan, the manufacturer adopted a dual-source strategy for critical components and further increased the number of suppliers for certain parts.

The delay was caused not by design or technology problems, but by "first-time yield issues" with a "very small number" of parts, experts say. Castings and forgings did not meet production standards, and scrap rates were higher than expected.

In September 2018 CFM was handing 12-14 engines per week to Airbus, which must rise to 16 by year-end, while shipments to Boeing are at 14 engines per week, with a target of 18-20.

AIII.6.2 Extreme dependencies from suppliers

It does not require many supplier issues to disrupt an engine assembly line, experts say. Another problem is that certain suppliers provide parts for multiple if not all engine OEMs.

MTU programme chief Michael Schreyogg confirms that supplier capacity for castings and forgings is "somewhat limited" across the aerospace sector and that opportunities do exist to broaden the supplier base.

Noting growth projections for the aviation industry, manufacturers outside the aerospace sector consider it highly attractive and are willing to make investments in technology and capacity in order to win long-term supply contracts.

MTU's GTF production planning began when the engine was in development. Schreyogg says the German manufacturer needed to restructure its industrial base for the programme – and a separate contract to supply turbine centre frames for GE's GEnx engine – because not only was MTU's output set to quadruple to around 4,000 shipsets across the decade though 2020, but new engine technology demanded a change in manufacturing processes.

Much of conventional engine parts production was transferred from the company's Munich base to a new plant in Rzeszow, Poland, while the headquarters was rejigged for highly automated blisk production and engine assembly.

AIII.6.3 Need for production changes and its consequences

It can be concluded that having enough time to develop stable production processes and stable supply chain circumstances is really key for success. This points to the fact that the production processes and suppliers should be changed in the middle of a ramp-up.

Production changes during the engine's development phase are "not a problem" if such moves are necessary to "manage and eliminate risk before the ramp-up", specialists say, but “changing during the ramp-up... will kill you."

MTU has made investments in its supply chain and worked closely with suppliers to ensure they have sufficient infrastructure in place. One needs to be deeply convinced that the partner can deliver the part in the right quality and volume.

In addition to a limited supply of castings and forgings, R-R says "increased demand on raw materials – and, in particular, powder metals – is causing a challenge". The UK manufacturer says blade availability is a "key challenge" and notes that increased maintenance activity as a result of the Trent 1000 in-service issues has "certainly... stretched our supply chain".

But notwithstanding the Trent 1000 situation, R-R insists it has taken "many steps" to reduce supply-chain pressures as "we have seen the potential for these challenges for some time".

After analysing all the problems associated with the production of turbofan engines, we can distinguish the following actions for successful production planning and achieving the planned output result: dual-sourcing; adding new partners to the supply chain; employing laser-welding techniques and exploring additive layer manufacturing for certain components to reduce reliance on a "very small number" of specialists for complex forgings, and using in-house component production capabilities.

Internal production capabilities diversify the supply chain, "help to reduce the cost of parts", and provide flexibility, R-R says. It adds that when blade demand was increased by efforts to deal with the Trent 1000 situation, the engine maker was "able to move production around within our owned capability, [thus] releasing our partners and suppliers to focus on ramping up their delivery of the most modern, complex parts".

GE says its "main production challenge" is "record demand for CFM engines overall, coupled with the speed of the Leap production ramp-up".

The joint venture's annual output has grown from around 1,600 CFM56s in 2015 to the 2018 year's targeted 2,100 engines, just over half of them Leap models. CFM delivered 77 Leap engines in 2016 – the year of the type's service entry – and 459 in 2017.

In 2018, the manufacturer intends to produce, for the first time, more Leap engines than CFM56s. For 2020, the plan is to deliver more than 2,000 Leaps a year, while CFM56 production will be wound down.

In addition to growing its supplier base, GE says it has established "intensive and continuous engagement with our suppliers at all levels" and set up "cross-functional teams to help identify and break production constraints". The US manufacturer also notes that it and Safran have in recent years expanded their manufacturing footprint and intensified efforts to introduce digital tools in order to raise engine output.

However, CFM's priority is to eliminate the delay in its existing ramp-up plan and stabilise production under current targets. The engine maker has repeatedly said it will not discuss with Airbus and Boeing potential further production increases before 2019.

AIII.6.4 Future technology

For new technologies, including ceramic matrix composites, the situation is the following: CMC production facilities are located outside Europe today and argues that engine manufacturers and suppliers in the region must establish production capacity for new technologies before they can be employed on future programmes.

Central to that effort will be the planned joint development of a Future Combat Air System (FCAS) between France and Germany. Specialists note that MTU's blisk technology for the GTF's high-pressure compressor is directly derived from the Eurofighter Typhoon-powering EuroJet EJ200 engine, for which the German manufacturer employed blisks for the first time on a serial production programme during the 1990s.

The planned Franco-German fighter will play a similar role maturing new technology that can be employed – on a large scale – on future commercial engines. A prime reason for governments to invest in FCAS is to establish manufacturing capabilities and capacity for future technologies so as not to be dependent on sources outside Europe. The development of a European-based supply chain will provide independence and stable and secure access to new capacities and technologies [62].

Annex IV Trade-off analysis on possible engine options for a new A380

AIV.1 Introduction

Improving the fuel efficiency of existing aircraft is an urgent task since it directly affects the costs of airlines. To ensure the competitiveness of the company, aircraft manufacturers seek to use new technologies for the modernization and modification of existing aircraft. In 2017, Airbus presented a development study for an enhanced A380, the "A380plus"[63]. The study includes aerodynamic improvements in particular new, large winglets and other wing refinements that allow for up to 4% fuel burn savings. The new winglets are designed to improve aerodynamics which directly affects the reduction of fuel burn by the aircraft. The optimised cabin layout allows up to 80 additional seats with no compromise on comfort. As a result, the overall benefit is a 13% cost per seat reduction versus today's A380. In addition, an optimised A380 maintenance programme and the enhanced cabin features were proposed.

The A380plus features longer maintenance check intervals and systems improvements, which will reduce maintenance costs and increase aircraft availability. The A380plus is an efficient way to offer even better economics and improved operational performance at the same time. A380plus is, of course, not NEO (new engine option), but it is a convenient, less steep path that leads to NEO.

The Emirates airline has been pushing Airbus for some time to offer an A380neo. Airbus has not moved forward on this because there are no new engines to enable a NEO. And the engines that are currently used on the A380, GP7200 from the Engine Alliance and Trent 900 from Rolls-Royce, do not meet the requirements for the new aircraft. There was an idea of using the Rolls-Royce XWB engine, but it did not work: it offers more thrust than is needed. And even if the engine were de-rated, it still weighs too much. A new generation of engines with a significant increase in fuel efficiency is what underlies the NEO.

AIV.2 A380 program forecasts

Back in 2018, the A380 release program itself was under threat[64]. The Emirates was the only possible carrier, which in the near future was still able to buy at least six A380 aircraft per year. The A380 program managers practically admitted that there is no market for the world's largest double-deck passenger aircraft and that Airbus had made a mistake in the early 2000s, deciding to design and manufacture an aircraft capable of carrying from 550 to 850 passengers. An erroneous evaluation of the prospects for transcontinental transportation was the reason for that. The Airbus considered that the rapid growth of passenger traffic on the planet would lead to an increased demand for flights between hubs – gateway airports with a large number of connecting flights, which include the Dubai airport. At the same time, the Boeing management assumed, on the contrary, that not so much large long-haul aircraft flying between several hubs would be in demand, as medium-sized airliners directly transporting passengers to various points of destination.

At the moment, the Boeing forecast is more correct. A380 orders for 2016 dropped to 15 aircraft. Though the most alarming signal was the lack of new orders in 2017. Moreover, the previous two orders were cancelled. Another negative factor was that the first deliveries of the aircraft to customers should have been in 2006, but in fact, began only two years later due to production problems (the only exception was the symbolic transfer of the first aircraft to Singapore Airlines in October 2007)[65]. As a result, the emergence of A380 aircraft coincided with the 2008 economic crisis, which led to a reduction in passenger traffic. Instead of buying expensive A380 and reducing ticket prices to fill it up, the airlines decided to buy smaller aircraft, which at the same time were easier to fill and pay for. An important factor was the appearance of such aircraft as Boeing 787 and Airbus 350 on the market, the range of which allows for long-haul flights that further reduced the market for the A380.

Another negative factor for the A380 program could be the appearance of the Boeing 777X on the market in 2020, which will be able to give almost the same opportunities to the customers as the A380.

At the moment, the A380 only fulfils the previous orders, amounting to 313 (although at the time of the program launch, the company estimated the potential market for these aircraft to be 1,400 units by 2020, which was planned to be shared with the Boeing 747 aircraft).

However, according to Aviation Daily, Airbus announced Feb. 14 that it is terminating the A380 program[66]. Emirates announced it will only take 14 more A380s instead of the 53 it had on firm order so far. The order is revised and now includes 40 A330-900s and 30 A350-900s, according to a new head of agreement. This leads to the end of A380 deliveries in 2021, Airbus said.

According to Emirates, the aircraft will continue to be operated "well into the 2030s." In spite of all the benefits and advantages of the A380, the refusal of further orders for it indicates the existence of economic reasons for the refusal of this aircraft.

In addition, the main problem of using the A380 was the engines. Since signing a firm order in 2018, the Emirates never reached an agreement with engine manufacturer Rolls-Royce, being currently, an official engine supplier for the Emirates, over the terms and performance guarantees for an additional Trent 900 order. The carrier had been unhappy with the price and the performance shortfalls it has seen on Trent 900 engines.

The partnership between Emirates and Rolls-Royce began in 2015 from the supply of Trent 900 engines for 50 aircraft. However, the British engine manufacturer struggled to achieve the quality control standards that it had previously guaranteed, collecting millions of lawsuits against the durability of its high-pressure turbine blades for the Trent 900 engine.

And the Engine Alliance company, a joint venture between General Electric and Pratt & Whitney, which until then had supplied A380 engines for Emirates, showed little interest in increasing production.

Unfortunately, in the light of these events, there is no basis for the release of the A380NEO. Refinement of the existing engines will not bring significant improvements, and the development of new engines needs time and money. Therefore, at this stage the best for

Airbus, if we assume that the situation may still change, will be the choice of existing engines, or those that are scheduled for release in the near future. Although CFM International's LEAP and Pratt & Whitney's PurePower GTF (PW1000G) engines have a bypass ratio of 12: 1, they are not suitable for this type of aircraft in terms of thrust performance. Therefore, the most optimal will be the expected engines of Rolls-Royce and General Electric.

Another issue is the feasibility of developing new engines for the Boeing NMA aircraft, taking into account the requirements for their possible use on the A380.

AIV.3 Engine options for A380NEO.

AIV.3.1 Rolls-Royce

In February 2014 the British company Rolls-Royce announced the development of Trent engines [67]. The code name of a new engine is the Advance. The bypass ratio shall be in excess of 11:1, the overall pressure ratio of more than 60:1.

There are several options for Advance engine development:

Advance 2 - 2-shaft jet engine [68]. Advance2 is an eco-system for demonstrating future products in the large cabin corporate jet market. Advance 2 demonstrates improvements in SFC performance while reducing noise and emissions. The pressure ratio of Advance 2 will be 50:1.

Advance 3 - 3-shaft jet engine[67]. Advance is based on the Trent XWB engine (Figure 66). In previous evolutions of the Trent, Rolls has grown engine capability by expanding the work done by the IP compressor and turbine. "As we grew the Trent family IP compressor, we grew the pressure ratio and gradually supercharged the engine, always keeping the high-pressure spool very similar," says Alan Newby, Rolls commercial engines advanced projects, chief engineer. "The big change from the core point of view is that the Advance reverses that, so we will put more on the high-pressure spool," he adds. The new Rolls engine will have a relatively larger high-pressure compressor with up to 10 stages (compared to six on the Trent XWB) and a greater pressure ratio, and it will be driven by a two-stage turbine against the single-stage used today. At the same time, the IP compressor will shrink from the eight stages of today's XWB to around four, while the IP turbine count will be cut to one from two stages.

The new configuration "provides a very lightly loaded high-pressure spool, which gives good efficiency and, more importantly, significant commonality with the follow-on core of the UltraFan." For the first time on any Rolls engine, Advance will have lighter composite-titanium fan blades.

In addition, Advance 3 will have optimized blades in one of the IP compressor stages and four HP compressor stages for constant changes within the flight range, and the air duct will be produced by additive manufacturing, i.e. 3D printing.

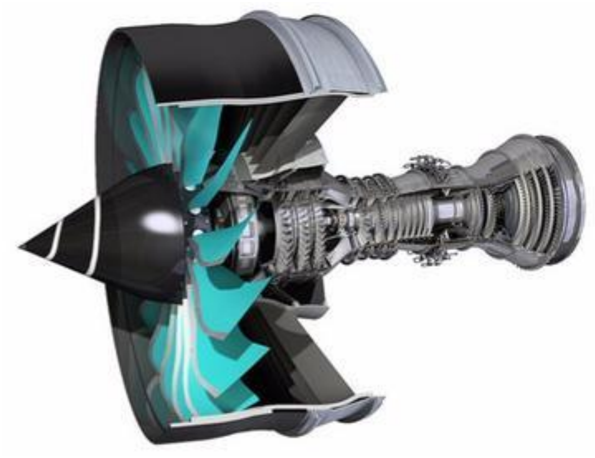


Figure 62. Advance 3[28]

As seen in Figure 63, a Ceramic Matrix Composite is used in Advance 3 for operation at high temperatures in sealing segments of the turbine stage 1 and its blades. Also, for the operation of rotating parts under high load conditions, hybrid ball bearings with ceramic rollers are used.

CMC components can operate at higher temperatures and require less cooling air while delivering a significant weight reduction[68].

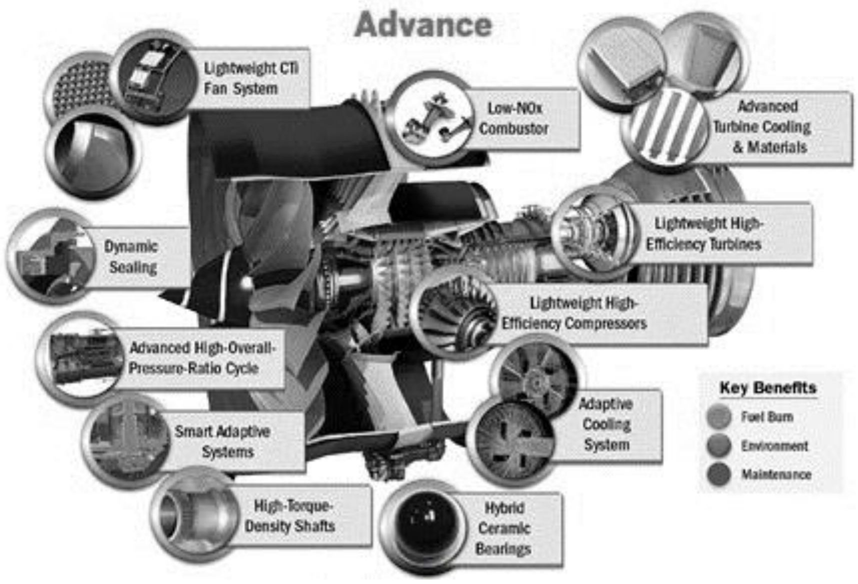


Figure 63. Advance 3 advantages[69]

A twin fuel-distribution system in a lean-burn combustor adds complexity through the need for hugely sophisticated control and switching system – not to mention doubling the amount of pipework, but it will deliver both improved fuel consumption and lower emissions of nitrous oxides [70].

The Advance 3 demonstrator engine, the core of which was attached to a Trent XWB fan system and a Trent 1000 low-pressure turbine, was sent to a test bench in 2017. The tests began in November 2017. In July 2018, the demonstrator core was already running at full power[71].

This event is an important factor in the development of the next UltraFan engine since its key technologies are based on Advance designs. UltraFan is a geared turbofan engine with a variable pitch fan system and a variable-area nozzle. Rolls Royce promises to improve fuel consumption by at least 25%. The bypass of UltraFan tends to a ratio of 15: 1, and the pressure ratio will be 70:1. This engine is suitable for use in wide-body and narrow-body aircraft due to a wide range of thrust options. Commissioning of this engine is planned no earlier than 2025.

UltraFan features a new gas generator architecture and a lean-burn combustor, which will contribute to the improvement of the fuel burn efficiency and reduction of emissions. The fan blades will be made of carbon titanium and a composite casing, which will reduce the engine weight by 430 kg or 750 pounds [68]. The engine has also a geared design that provides productive power with a high bypass ratio.

The UltraFan engine will retain the Advance gas generator, but will not be a three-shaft design [67]. It will rather be a "two-and-a-half" configuration. UltraFan will also have a new form of fully integrated, slim-line nacelle design. As the fan system is designed to vary pitch in all phases of flight, including landing, the nacelle will not include a thrust reverser.

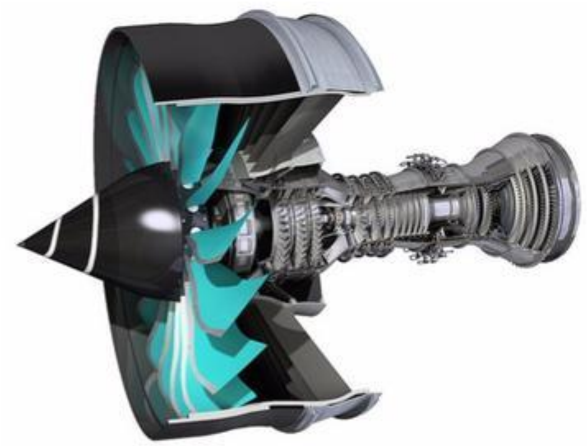


Figure 64. UltraFan[68]

Outstanding technologies in the program are composite titanium fan blades, as well as Power Gearbox technology, which was introduced into the UltraFan demonstrator to achieve the maximum optimum efficiency of the engine gas generator and the fan.

Figure 65. Carbon-Titanium blades Advance and UltraFan engines [72]

The Power Gearbox will play a central role in the company's next-generation UltraFan® engine, helping to deliver improved efficiency over a wide range of thrusts. Rolls Royce's Power Gearbox is designed to run all the way up to 100,000 horsepower and future demonstrators are expected to achieve these levels. [73].

The Power Gearbox has a planetary design. It is designed to allow the shafts at the core of the engine to run at very high speeds while allowing the fan at the front of the engine to run at a slower speed.

As well as high power testing, the Power Gearbox is also undergoing Attitude Rig testing, which simulates the effect of the gearbox being on the wing of an aircraft in flight, through phases such as take-off, climb, banking and descent.

The Ultra High Bypass Ratio (UHBR) engine demonstrator, UltraFan® is being developed by Rolls-Royce in cooperation with Airbus within the framework of Clean Sky's ENGINE ITD, European Union research program aimed at developing technologies to reduce emissions[74]. Among the elements of the UltraFan program are ground and flight test planning. The tests will be performed on a Rolls-Royce test bench.

Also, the key moment in the UltraFan project is the analysis of the effect of the engine and wing integration. Therefore, at Airbus, the current focus is around the integration of the engine and the airframe. The significant increase in the fan diameter, compared to existing engines, has necessitated the design of new architecture and technology enablers to allow it to be integrated onto an aircraft.

The main objective of the program is to design the pylon, thermal management and the nacelle aspect, but also to perform the calculations and tests on significant components such as the thrust reverser unit, the nacelle coupling effect of the engine and the wing, and also the aero-acoustic characterization of this engine as well as the jet noise and exhaust coming out from the engine.

Together with Rolls-Royce, and in the frame of Clean Sky 2[75], Airbus has produced a number of the innovative nacelle and engine architectures that are compatible with UltraFan from Rolls-Royce, and those nacelle and engine architectures have now reached the concept freeze, so we've now attained TRL3.

By July 2018, the concept design of the UltraFan demonstrator was frozen. Ground testing of the engine should start in 2021.

Summarizing, we can say that the UltraFan engine, available from 2025, will include:

- High combustion efficiency and low emissions due to the new design of the engine combustor.
- Weight reduction due to the use of carbon titanium (CTi) in fan blades and composite casing.
- The increased efficiency due to the use of ceramic matrix composites (CMC), which are heat resistant and require less cooling air.
- The increased rotational frequency of the gas generator, due to the use of a geared fan.

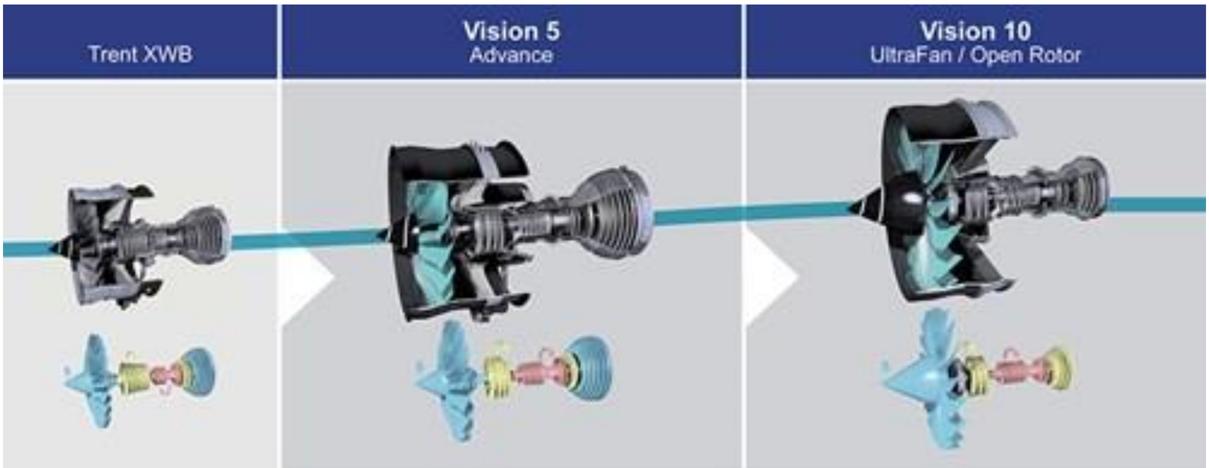


Figure 66. The evolution of the Trent XWB to the UltraFan[75]

Table 2. General characteristics

	Trent 1000	Trent XWB	Advance 3	UltraFan
Overall pressure ratio	50:1	50:1	60:1	70:1
Bypass ratio	10	9,6	11	15
Service entry	2006	2010	2020	2025

It is also worth noting that Rolls-Royce is committed to fulfilling ACARE and Flightpath2050 goals. As seen in Figure 67, Advance and UltraFan engines will show a reduction in CO_2, NO_X emissions and noise:

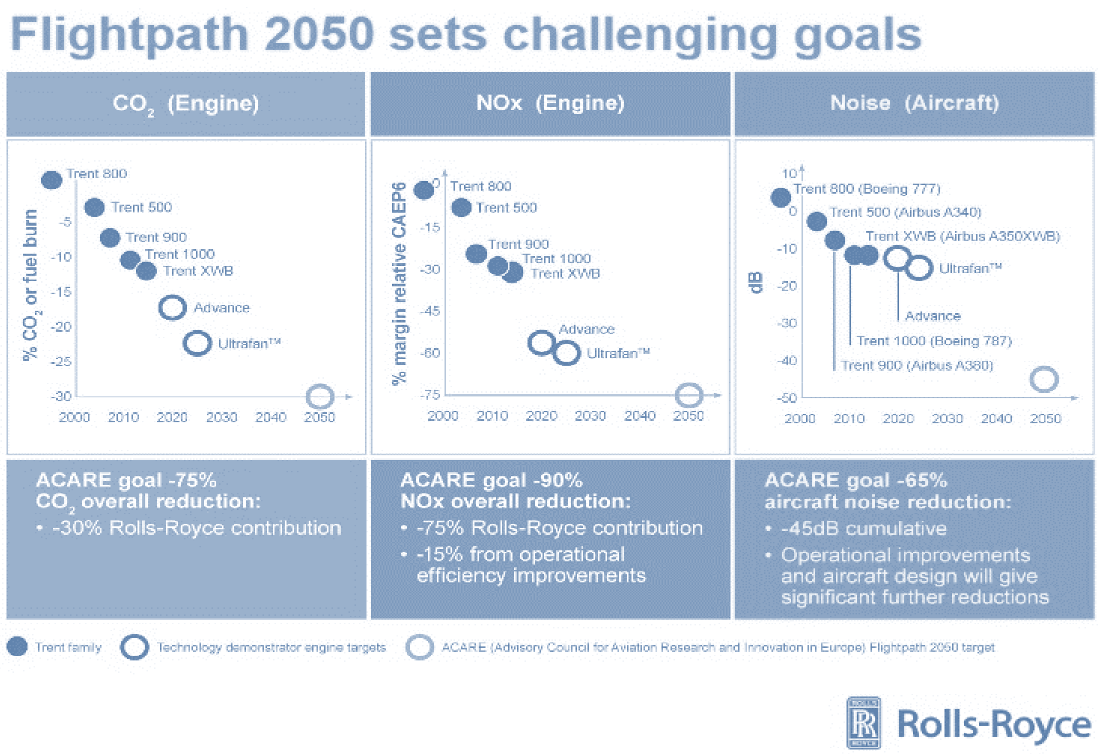


Figure 67. Challenging goals[56]

AIV.3.2 General electric

The General Electric GE90 is a family of turbofan engines for civil aviation [15]. It is designed for use in large Boeing 777 airliners. Initially, the GE90 was intended as a replacement for CFM International CFM56, however, with the start of the Boeing 777 project, was enlarged for 777.

The GE90 was launched in 1993, and the first flight took place in November 1995. There are many modifications of the GE90. The GE90-110B1 and GE90-115B engine models can provide thrust over 57 tons (125,000 lbf).

For the first time in the history of commercial aviation, fan blades made of composite materials were used in the design of the GE90 engine. Namely, of carbon fibre and epoxy matrix. They are three times lighter than titanium blades and twice as strong. Special aerodynamic bending of the blades provides a higher airflow rate while producing less noise than counterparts with the classical design.

Figure 68. GE90-115B blade New York Museum of Modern Art[76]

Further evolution of the GE90 engine is the GE9X [76]. It is an engine with a high bypass ratio (10:1), a larger fan, in the design of which ceramic matrix composites are used. Specific fuel consumption is improved by 10% compared with the GE90-115B.

The design of the GE9X engine used a lot of parts made of heat-resistant and lightweight ceramic matrix composites capable of withstanding temperatures up to 1400 degrees Celsius, which significantly increased the temperature in the engine combustion chamber. With one-third of the metal alloys density, these ultralight materials reduce the weight of the engine, increasing the weight perfection and service life of the engine [77](Figure 70). Due to the fact that these materials are more heat-resistant than metal alloys, they require less cooling air, which leads to improved engine fuel efficiency.

The higher the temperature can be obtained in the engine, the greater the efficiency it demonstrates. At higher gas temperatures, fuel burns more completely, so fuel consumption and emissions are reduced [76].

The reliability of parts made of ceramic matrix composites, and of the engine as a whole, was confirmed by tests. While the engine was in operation, such amount of solid matters and dust was thrown into it that could be ingested in actual conditions during three thousand take-offs and landings [78]. Debris disposal system of the GE9X engine effectively removes solid matters to protect the main components (Figure 70).

Modern 3D printing technology had great importance for the manufacture of some engine components. With its help, parts of such a complex shape, which cannot be obtained by traditional machining, were created.

The GE9X also includes 16 fourth-generation carbon-fibre fan blades at the front of the engine that feeds air into an 11-stage high-pressure compressor with a 27:1 pressure ratio, which also boosts the engine's efficiency. The 16 blades of the GE9X fan are the minimum number of blades used in the engine for a wide-body aircraft. The 11-stage HP compressor is made with the first five stages in the form of a blisk and with new 3D aerodynamics in all stages (Fig. 9). The LP turbine blades of the GE9X engine are made of titanium aluminide, which is stronger, lighter and more durable than its nickel analogues. And powder alloys are used in the high-pressure compressor and turbine. The GE9X also includes a three-stage booster to increase airflow and efficiency. And by the time the engine is commissioned, the composite blades of the 4th generation will have more than 100 million flight hours.

The GE9X engine provides a reduction in CO_2 and NOx emissions of about 30% below the environmental regulations predicted for the next decade (CAEP 8), as well as noise reduction of 8 dB.

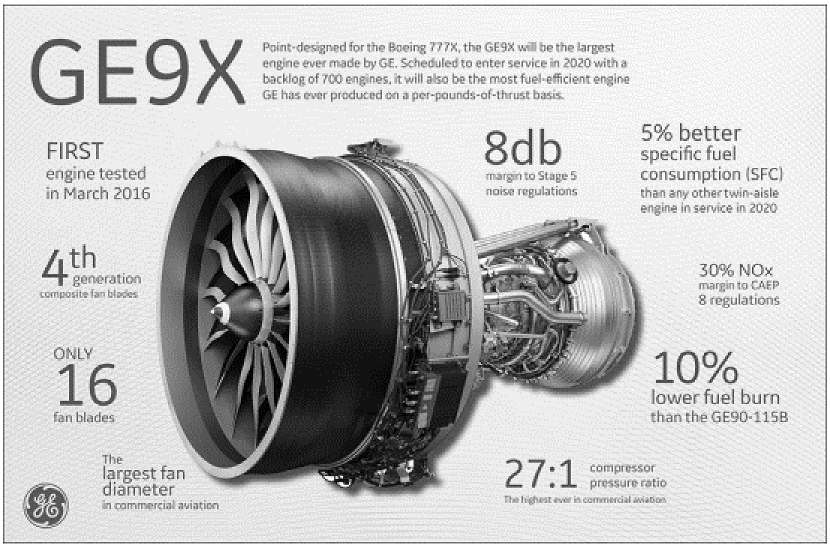


Figure 69. Engine GE9X[79]

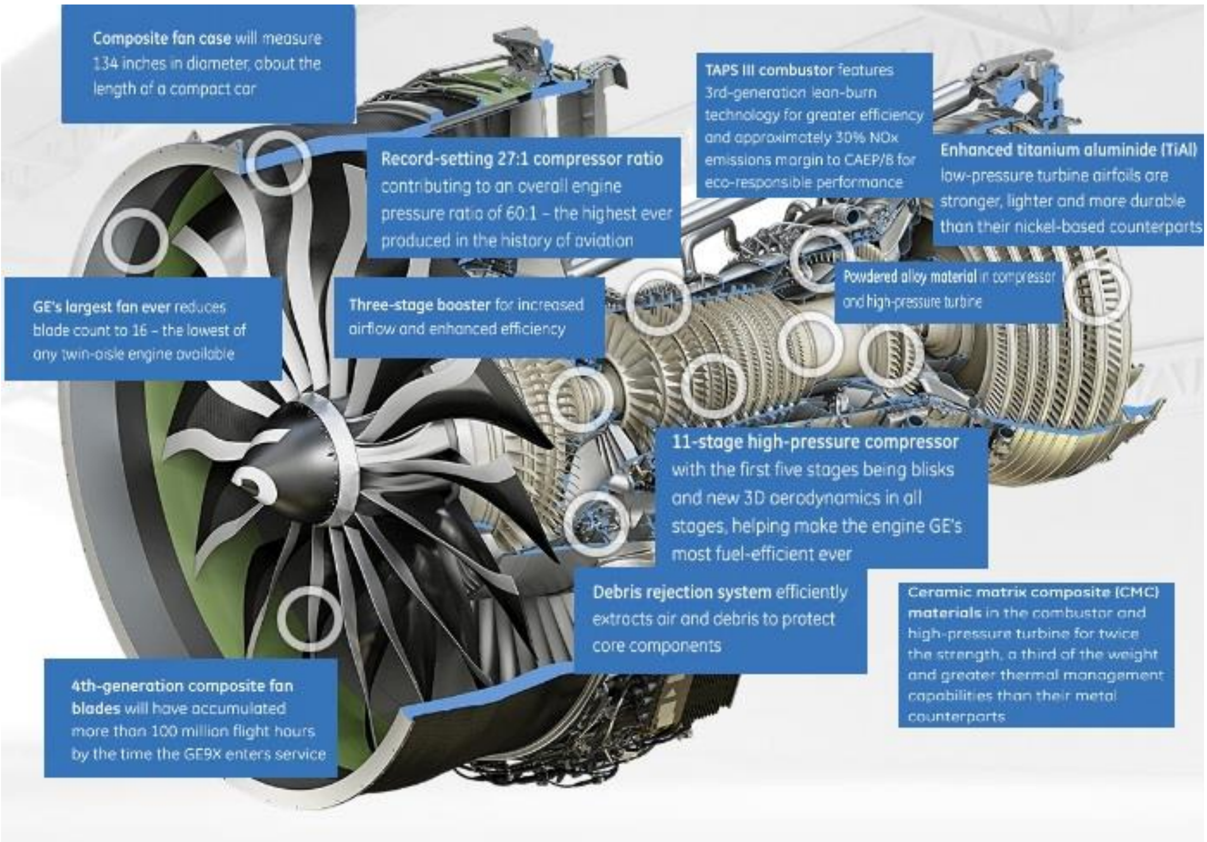


Figure 70. Engine GE9X [80]

General Electric began the first tests of the GE9X engine in March 2016. This testing was conducted to check the aerodynamic, thermal, and mechanical characteristics of the engine.

Now the GE9X engine is in the second stage of air tests, which will last the entire first quarter of 2019[81]. This testing will help General Electric to come close to the goal of obtaining the FAA (Federal Aviation Administration) engine certification in 2019. The first flight is expected in 2019, and the delivery, after certification, in 2020.

*Table 3. General characteristics (Note: * modification -115B)*

Parameter	**GE90***	**GE9X**
Max. Take-off thrust (lbf)	115.500	105.000
Overall pressure ratio	42:1	60:1
Bypass ratio	9	10
Fan diameter (in)	123	134
Number of fan/low-pressure/high-pressure compressor stages	1+4+9	1+3+11

Parameter	GE90*	GE9X
Number of high-pressure/low-pressure turbine stages	2+6	2+6
Entry into service	1995	2020

Thus, it is possible to identify some of the similarities and differences of the engines under consideration. The Rolls-Royce engines differ from General Electric in compressor architecture. The Rolls-Royce design consists of high-pressure, intermediate-pressure and low-pressure compressors, while GE engines use high-pressure and low-pressure compressors. Unlike these two-shaft engines, in which the fan and low-pressure (LP) compressor are driven by the LP turbine, the fan alone is driven by the LP turbine in the Trent. In place of the conventional LP compressor, the three-shaft design has an IP compressor, which is driven by an IP turbine. Both two- and three-shaft engines have similar high-pressure spools, though there are fewer stages in the three-shaft compressor and turbine. The Rolls-Royce three-shaft engines are a configuration with three spools, operating at different speeds. Rolls-Royce claims that its three-shaft design reduces engine length and makes the engine relatively cooler, requiring less maintenance. In such a configuration, the number of variable stages of the guide vanes necessary for ensuring gas-dynamic stability can be reduced or eliminated. This solution allows for increasing the weight perfection of the engine.

One of the key elements of the Rolls-Royce UltraFan engine is the use of a low-speed geared fan (Power Gearbox).

The design of the fan blade of the Rolls-Royce engine consists of a carbon body with a titanium leading edge. Fan blades of the General Electric engine are also made of a hardened epoxy filler and a carbon fibre matrix. The uniquely curved profile of the fan blade allows for an increase in airflow rate, making it quieter and more efficient, developing high thrust. In both cases, the use of composite materials reduces the weight of the engine and provides improved strength of the engine elements.

Both Rolls-Royce and General Electric use heat-resistant and lightweight ceramic matrix composites that require less cooling air in turbine designs.

Both Rolls-Royce and General Electric use 3D printing technology to manufacture very complex parts.

All engines show a reduction in CO_2 and NOx emissions and a decrease in noise, but UltraFan will be the leader in this area with its specified indicators: reduced CO_2 by 25% and NOx by 60% and a decrease in noise indicators by 15-20 dB.

AIV.4 Conclusions

In order to be a competitive new wide-body aircraft, it is crucial for the A380 to improve its economic efficiency. Modernization of the current engines cannot provide high indicators of efficiency and increase their service life. Design modifications of the aircraft wing and the use of new winglets will allow achieving an improvement in fuel consumption by 4%. In order to reduce fuel consumption significantly, it is necessary to use engines of a new generation with a considerable increase in fuel efficiency. At the moment, the engine in large part determines the fuel efficiency of the aircraft. Nevertheless, it is still necessary to consider comprehensive measures, namely the use of new engines and the improvement of aerodynamic quality of the airframe, weight perfection of the airframe, and the engine, and their systems. In addition, these will require significant changes in the design. Time for research and development, as well as material costs, will also be required.

Nowadays, major engine manufacturers seek to improve the architecture of engines for new generations of long-haul aircraft, in particular, the A380. The development of new engine concepts is a long and costly process, often limited by the emerging unknown problems in applying new technologies. Also, the new engine concept should provide significant improvements in fuel consumption, reduce emissions and noise. The time required to achieve the technological readiness of the engine and the commissioning date of the engine is not clearly defined.

The aerospace industry is the world leader in solving the problems related to technology and efficiency. The tasks of improving the state of the environment are tougher than ever and must be carried out. The ACARE's vision for the future, Flightpath 2050, sets clear environmental technology objectives for aircraft in comparison with 2000. Achievement of these objectives will be carried out by means of aeronautical engineering and engine technology, as well as by improvements in airline operations and air traffic management.

All engines showed improved fuel consumption, reduced CO_2 and NOx emissions, and reduced noise levels. All manufacturers seek to carry out new work in the field of high-temperature technologies. They also strive to apply 3D printing in order to reduce development time by means of rapid project implementation into components and to manufacture completely new shapes of parts that could not be done before. Nickel and titanium alloys, ceramic matrix composites and carbon composites are actively used in companies' developments. All these play a role in reducing weight and improving performance at high temperatures. Despite these, there are some differences in performance:

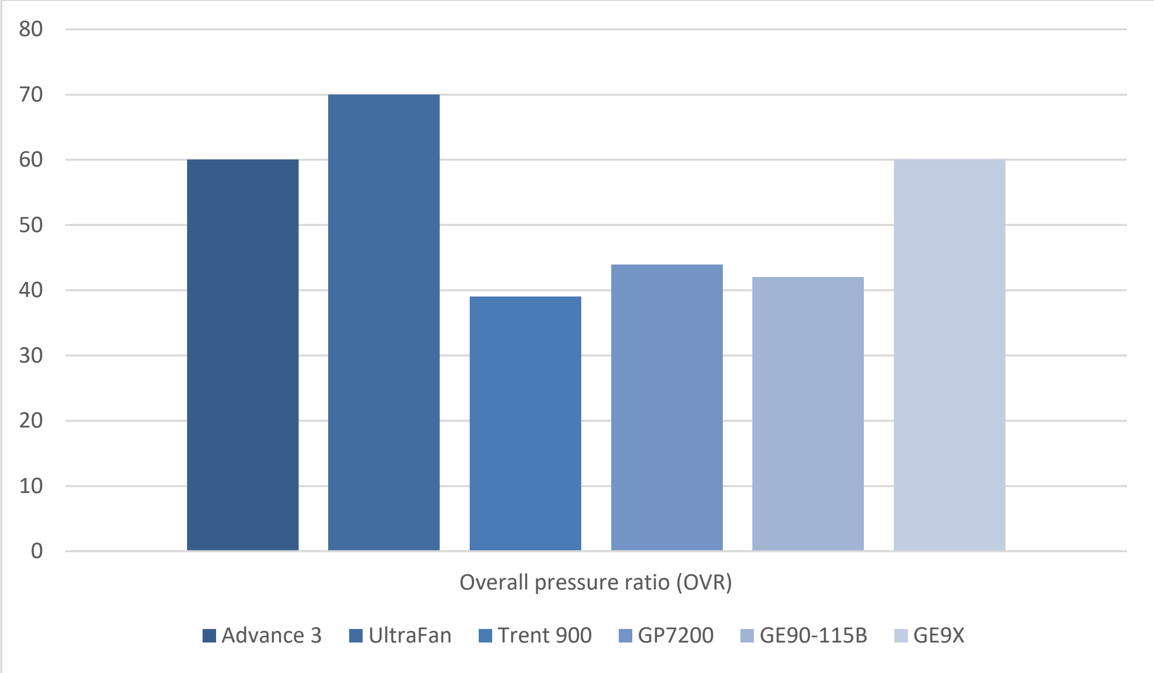


Figure 71. Overall pressure ratio

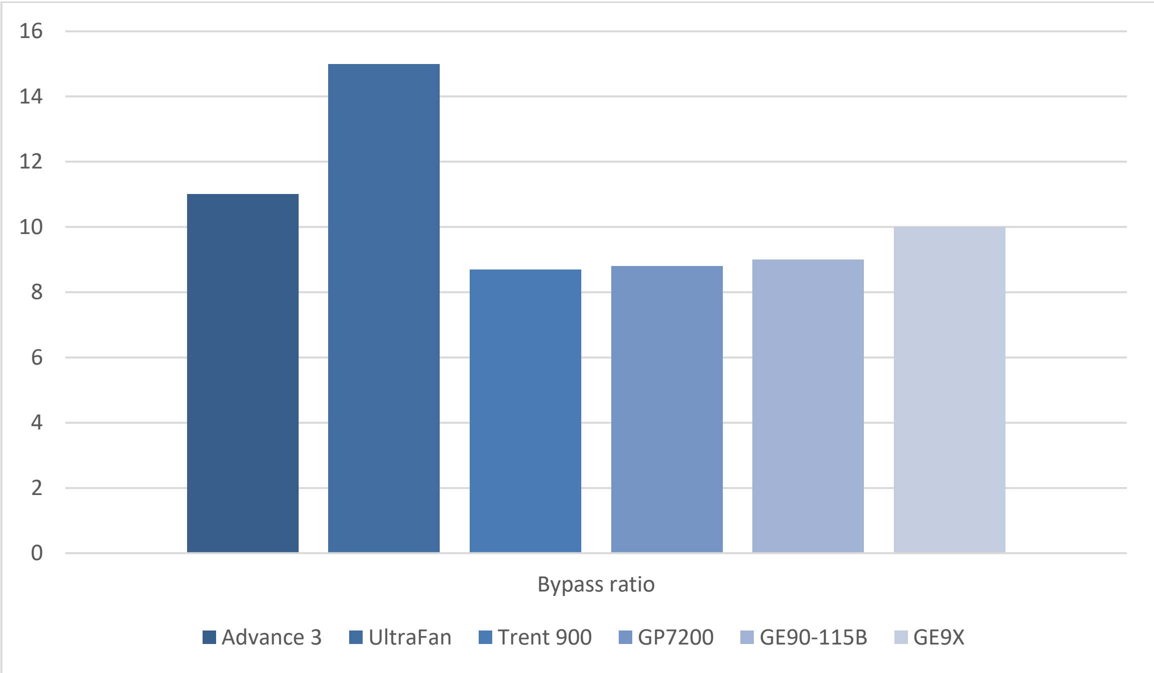


Figure 72. Bypass ratio

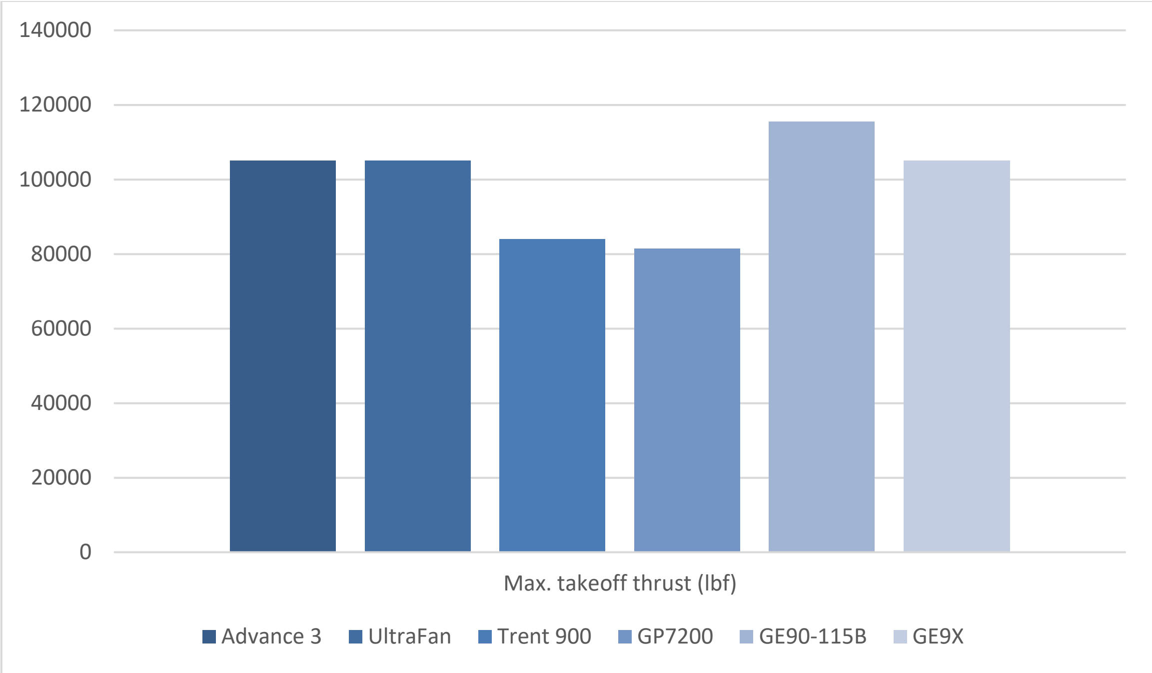


Figure 73. Max. takeoff thrust (lbf)

The CFM International LEAP engines present a good platform to develop solutions for General Electric. Although they work without serious complaints and do not bring problems, both financial and image ones, to their creators and users, in terms of thrust these engines are good for use in narrow body airplanes and are not suitable for the A380.

Although the Pratt & Whitney PW1000G series engines have a lower weight and greater efficiency compared with the LEAP engines, they still have a number of problems arising during their operation. These engines are also suitable for single-aisle aircraft. As previously reported, in October 2017, Pratt & Whitney announced work on the creation of the next-generation turbojet engine with a bypass ratio much higher than 12.2, as was the case with the PW1100G engine. However, more detailed information was not disclosed. Perhaps the new Pratt & Whitney engine is being developed and could have been used as an engine option for the new A380, but it's too early to talk about it.

According to the class of thrust, it is possible to use the General Electric GE90 and GE9X engines. However, in terms of bypass ratio, they are inferior to Rolls-Royce engines. In terms of pressure ratio, the GE9X is comparable with Advance but inferior to UltraFan. Engine weight is another very important indicator. The GE9X weight was not officially announced yet, but as the author notes [82], the engine will be slightly heavier than its predecessor, the GE90, what makes these engines an undesirable option for new A380NEO, as was the case with the Rolls-Royce Trent XWB.

Considering the signed agreement between Rolls-Royce and Airbus for the Clean Sky project, the Advance 3 engine is a good option for the new A380, showing high bypass ratio, pressure ratio and thrust. However, according to the first two characteristics, it is inferior to its successor – the UltraFan engine. Using composite materials in fan blades instead of the usual design with hollow titanium blades, the Rolls-Royce announced a reduction in weight of about 340 kg per engine, which is another advantage over General Electric engines. And for now, the only drawback of the UltraFan engine is its commissioning date, scheduled for 2025.

Although the integration of new engines is a complex engineering task due to significantly increased engine diameters, as well as the investment of large cash expenditures, the further advantages may be much more profitable. It is very important to reduce fuel costs. And their share in total costs will only increase. According to the International Air Transport Association (IATA), in 2015, $ 181 billion was spent on fuel throughout the world. This is the lowest figure since 2005. However, according to international forecasts, the price of fuel will rise. Therefore, even the smallest increase in engine fuel efficiency makes its usage economically viable. The fuel efficiency advantage will allow carrying more passengers and thus generating more revenue. Even 1% of fuel efficiency on long-haul flights, namely, the purpose of A380 type aircraft, can reach up to $ 1.7 million per plane. And carbon emissions can be reduced by 4,000 tons per year. Moreover, even for the government-supported Emirates Airline, the largest and most important customer of the A380, having the geographically advantageous location of a country in a bay rich in oil, the fuel economy is becoming an increasingly important factor.

As already mentioned, the further development of the A380 program is in great doubt due to the lack of orders. This is an important factor for engine manufacturers. It is not advisable to invest significant means in engine development for an aircraft whose program is at the finishing stage. Analysis and postponed decision to launch the Boeing NMA program for 2020 [83], the engines for which could affect the appearance of the A380NEO, allow to make a conclusion that the engine for the A380NEO will not be presented in the near future.

Annex V Annex V. Insight on routes flown by mid-sized aircraft

AV.1 Introduction

Nowadays more than 6000 airports exist in the world [84]. The location of the airports is shown in Figure 74. As can be seen from the figure, the highest density of airports is in Europe, North America, South Asia and South Africa.

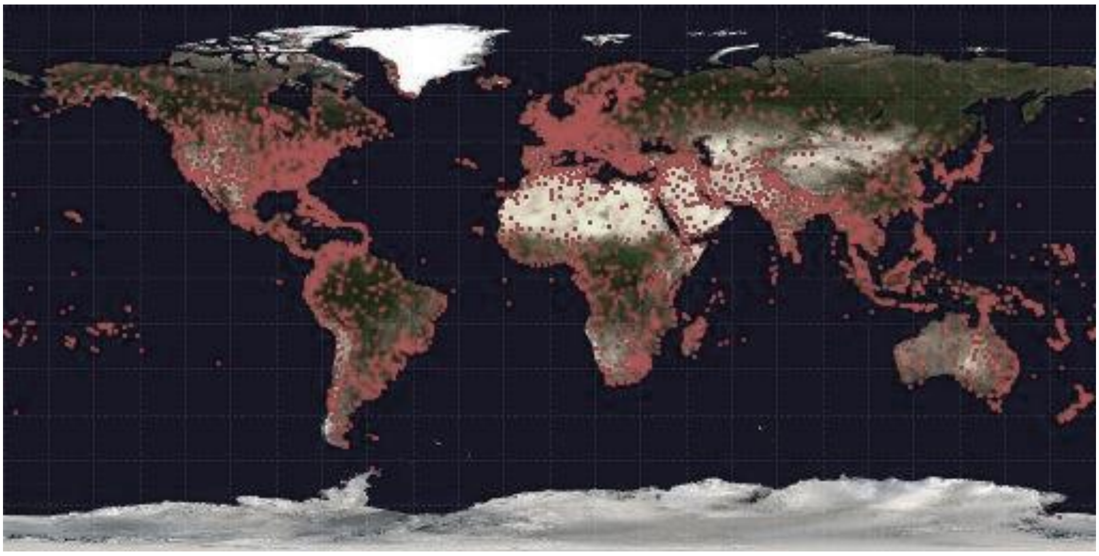


Figure 74. Airports world locations map[84]

Scheduled flights of aircraft are made via the great majority of these airports. Now there are about 58,000 air routes, which are shown in Figure 75.

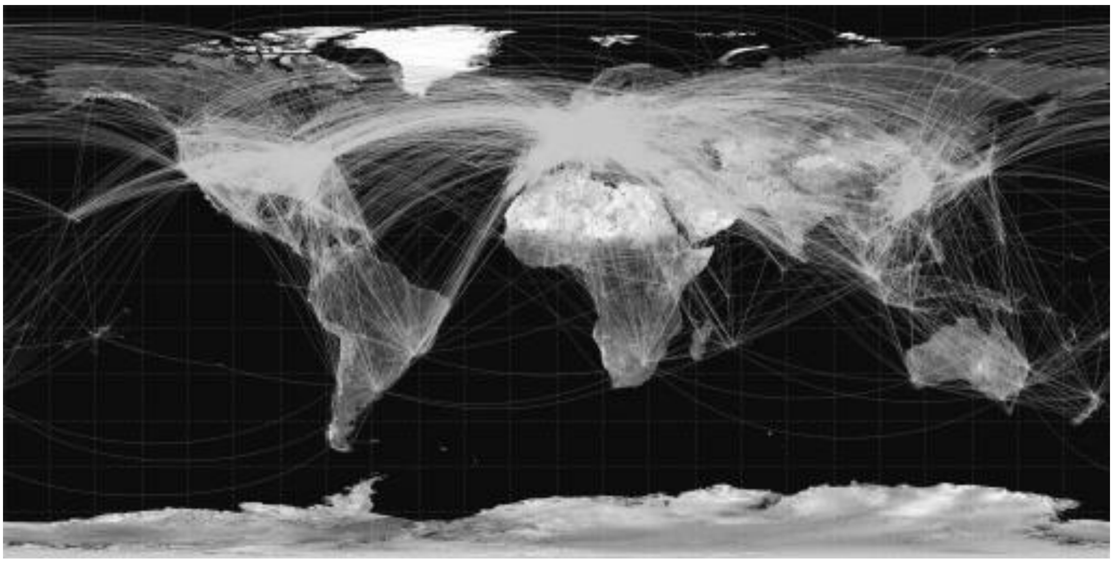


Figure 75. Air routes map [84]

The air route of the aircraft is determined by the passenger's demand on this route, as well as the capabilities of the aircraft. So, according to the Boeing information [85] after the release of the B787 Dreamliner, the number of routes that were introduced due to the appearance of a new aircraft amounted to 586. The appearance of new routes by year is shown in Figure 76. The flight pattern of these routes is shown in Figure 77.

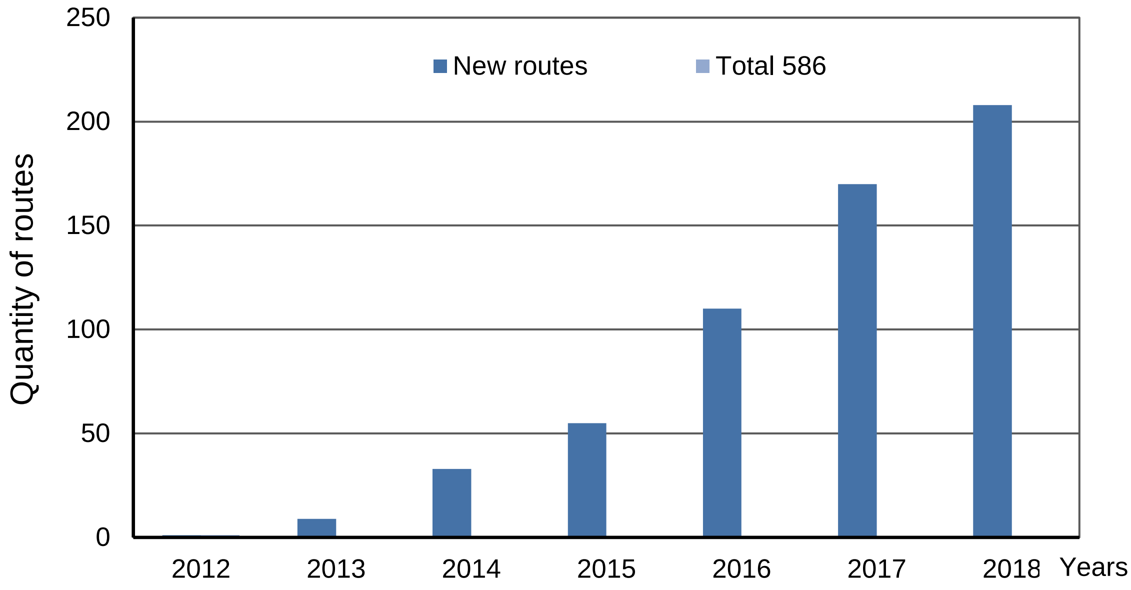


Figure 76. New routes appearance due to B787 release

Figure 77. B787 Dreamliner new routes pattern

As can be seen from the pattern shown in Figure 77, the great majority of the introduced new routes have a considerable range. However, at the same time, airliners can also use this airliner for short-haul flights.

AV.2 Aircraft types distribution by routes

Along with new aircraft, the airline fleet consists of earlier production aircraft. One of these is the Boeing 757. As stated in [86] 2000 might have been the height of B757 flights. The aircraft still services a handful of North American, European and transatlantic routes today. 2011 was the peak year for Europe to United States B757 service within the last eight years, but the number of airlines operating routes has actually increased since then. Though many of the aircraft have been taken out of the skies, a look at recent trends reveals the B757 is still used to support new and existing routes to and from major U.S. and European hub airports. The airlines using this aircraft today include American, Delta and United.

As transatlantic travel continues to increase in popularity, major U.S. carriers have adopted B757s to supplement developing and established routes to some of Europe's largest airports, including Frankfurt, London Heathrow and Paris Charles De Gaulle. A more specific example is Dublin, where seven markets will be serviced by B757s in 2017 compared to only three in 2011 [86].

The fleet also plays an important role in the fight for market share between LCCs vs. legacy carriers. Competition between legacy carriers remains high, and as passengers increasingly flock toward low-cost airlines, B757s play a useful role balancing for legacy carriers, providing both supplemental capacities on trunk routes and operating the thinner secondary hub markets.

Usage of the B757s fleet has certainly dropped from its peak, as there are 315,503 scheduled flights planned in 2017, down roughly 70% from the year 2000. As the largest North American operator of the aircraft, Delta Air Lines has just under 110,000 flights scheduled in 2017, down 44% compared to 2011. According to CAPA, the airline currently has around 126 of the aircraft type in operation.

In order to assess the distribution of Boeing 757 fly routes by range, a statistical evaluation of the distribution of routes by the range in the US domestic market was carried out. Figure 78 shows part of the aircraft flying on routes less than 1000 nautical miles and from 1000 to 3000 nautical miles.

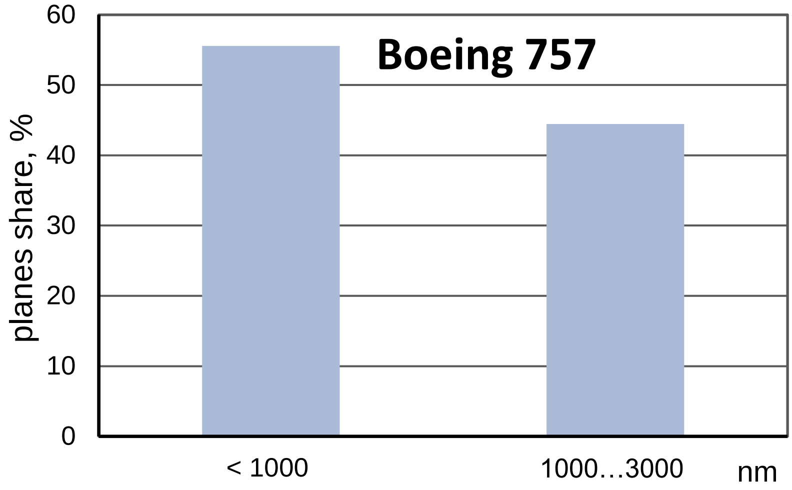


Figure 78. Boeing 757 routes distribution by the range

North America remains the major region of use for the aircraft and will account for over 62% of total planned flights this year. Comparatively speaking, in 2000, North America held 64% of all B757 flights. Collectively, Western Europe and North America have 82% of the aircraft planned services in 2017, a similar proportion to that of 2000 [86].

Also based on data on the distribution of aircraft by air routes, provided by Flight Aware[87], the use of medium-haul aircraft on routes of different ranges was analysed. For example, the share of Boeing 787-8 and 787-9 used on routes of different ranges is not the same and is shown in Figure 79. The data analysis shows that this type of aircraft is mainly used on routes longer than 3000 nautical miles, which corresponds to its purpose. But it is not a typical situation for every case. Most aircraft are mainly used on short- or medium-haul routes, such as the Airbus A330-200 (Figure 79).

In this study, according to Flight Aware, the relative average range of air routes for various types of aircraft was also estimated. The relative average range of the air route should be understood as the ratio of the average range of the routes on which this type of aircraft flies to the maximum flight range of this aircraft. The obtained values are presented in the form of a diagram in Figure 80 as a percentage of the flight range of the specified aircraft.

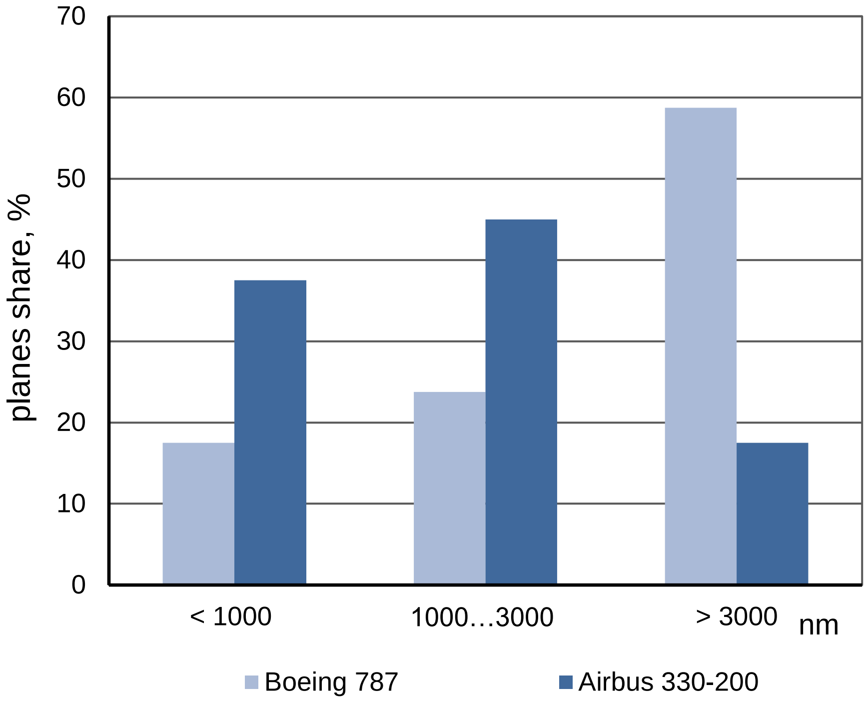


Figure 79. B787 and A330-200 distribution by the routes of different range

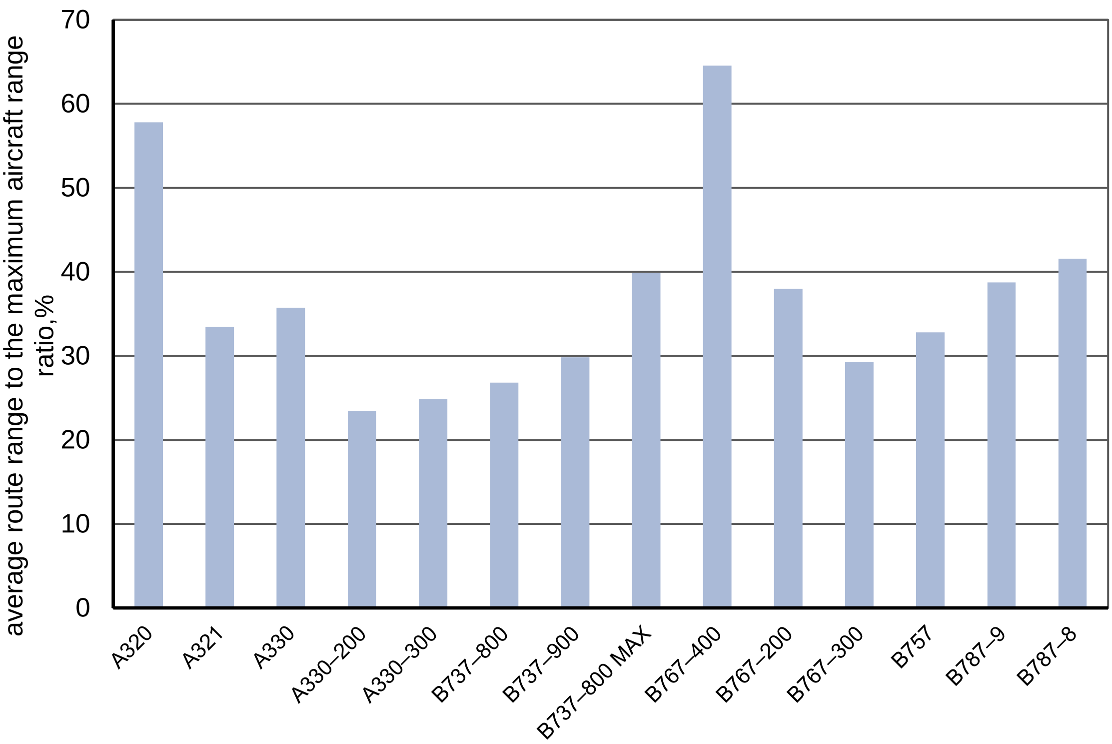


Figure 80. Relative average flight range for various aircraft

Analysis of the data shown in Figure 80 allows us to conclude that a greater number of aircraft performs flights, the range of which is less than 40% of the maximum flight range. This is due, apparently, to the desire of companies to reduce the time of preparing the aircraft for departure and to avoid the need for refueling.

To assess the distribution of the types of aircraft that fly on the routes of different ranges, sampled information was taken from the data provided by FlightAware. The information was sampled for the types of medium-size aircraft, namely B757, B767, B737, B787, A330, A321.

Where possible, various modifications were evaluated. As a result of processing statistical data, aircraft distributions were obtained on routes of various ranges, namely routes less than 1000 nautical miles, routes longer than 1000 nautical miles, but less than 3000 nautical miles, and routes exceeding 3000 miles.

The general distribution of the aircraft en-route is shown in Figure 81 as a percentage of the total number of aircraft. Analysis of the data presented in Figure 81 allows us to conclude that a large number of aircraft is used on short-haul routes and does not use the capabilities of the aircraft.

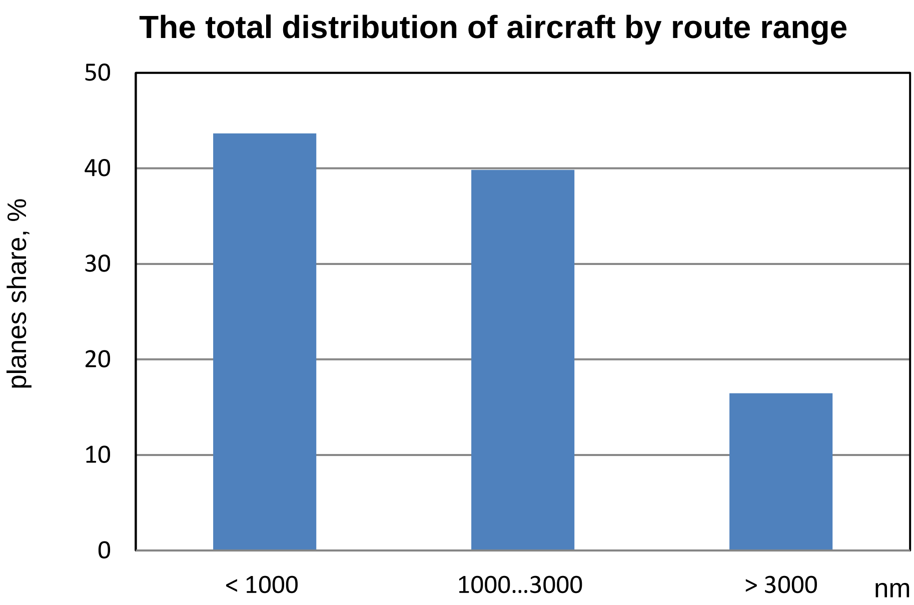


Figure 81. The total distribution of aircraft by route ranges

This segmentation (Figure 81) was rather conventional. It is convenient to estimate the distribution of aircraft flying on various routes, which are used in the sampled information, using the data shown in Figure 82.

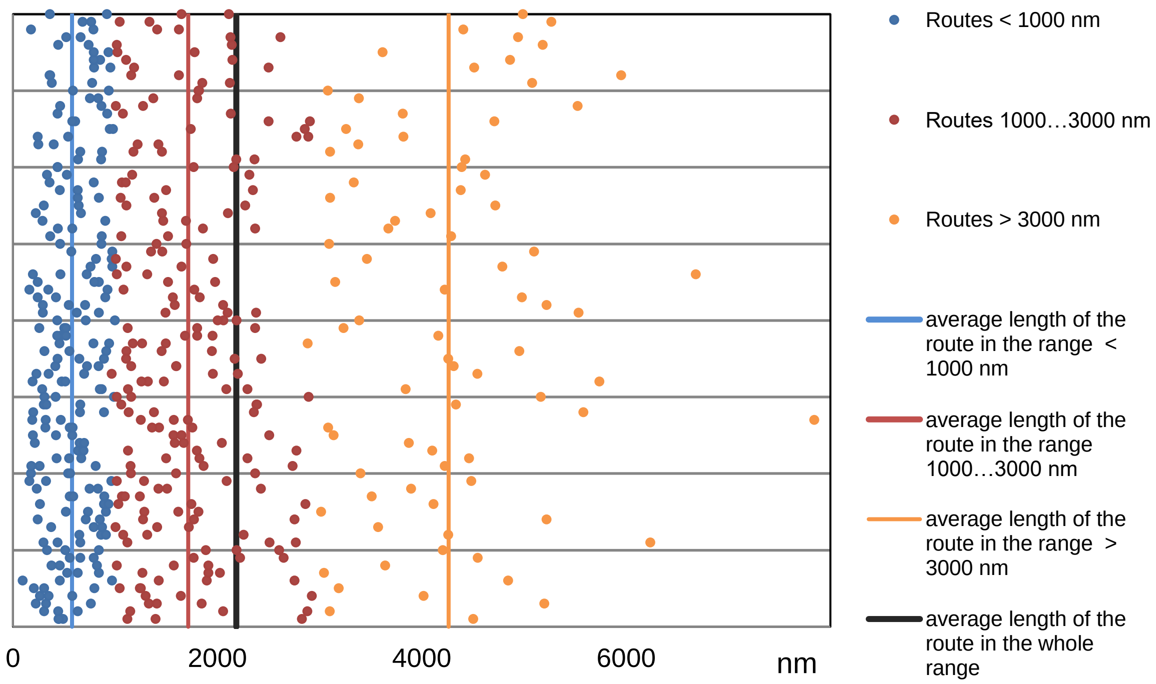


Figure 82. Distribution of routes of different range and average values of ranges by routes segments and in general

According to the results of processing the data shown in Figure 82, it is established that the air routes average range for the types of aircraft presented in this study is:

- in the range less than 1,000 nautical miles - 579 nautical miles;
- in the range from 1000 to 3000 - 1716 nautical miles;
- in the range more than 3000 nautical miles - 4264 nautical miles;
- in general, for the routes under consideration - 2186 nautical miles.

In addition, in the course of processing the statistical data, the distribution of aircraft types that perform flights was obtained over various flight ranges, and over the entire range as a whole. Distribution data are presented from Figure 83 to Figure 86.

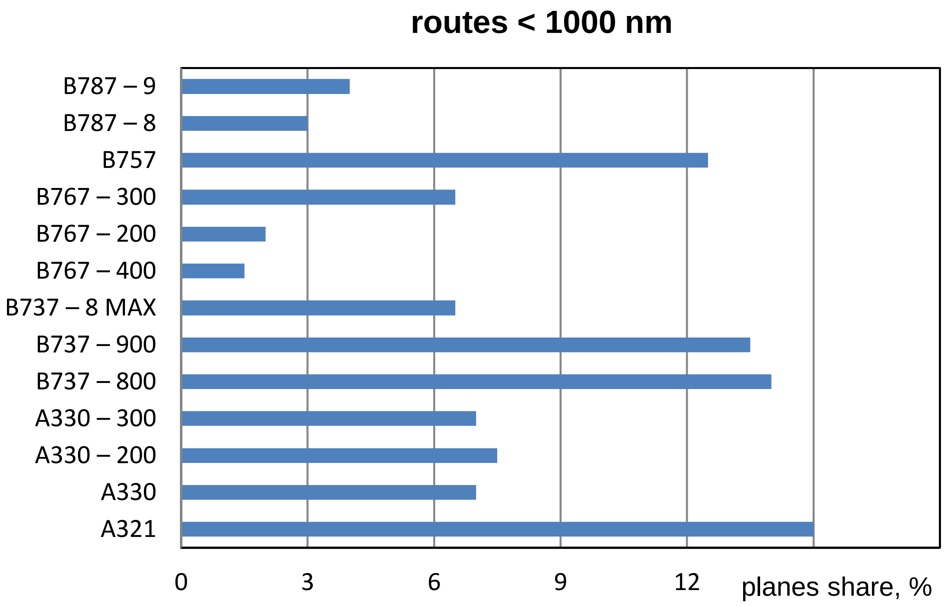


Figure 83. The distribution of aircraft types in the selected air routes range

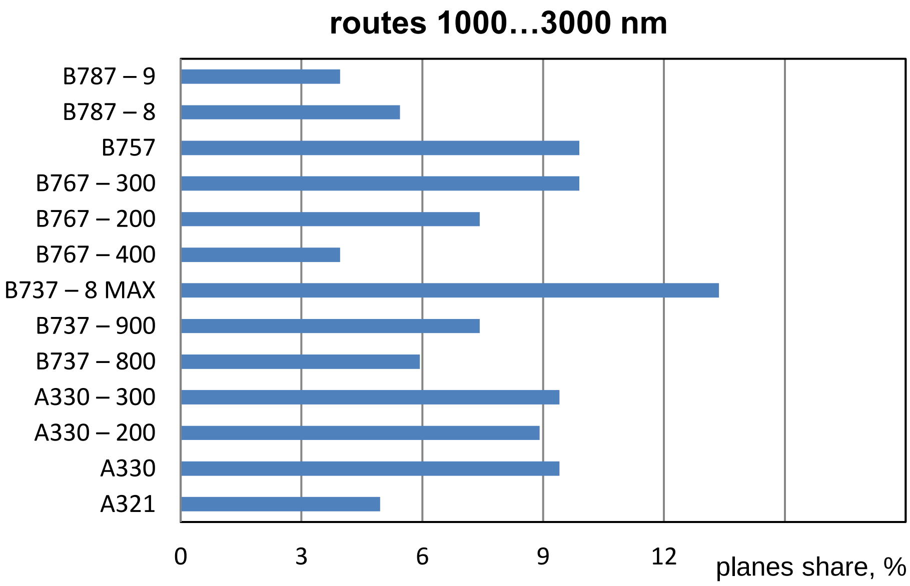


Figure 84. The distribution of aircraft types in the selected air routes range

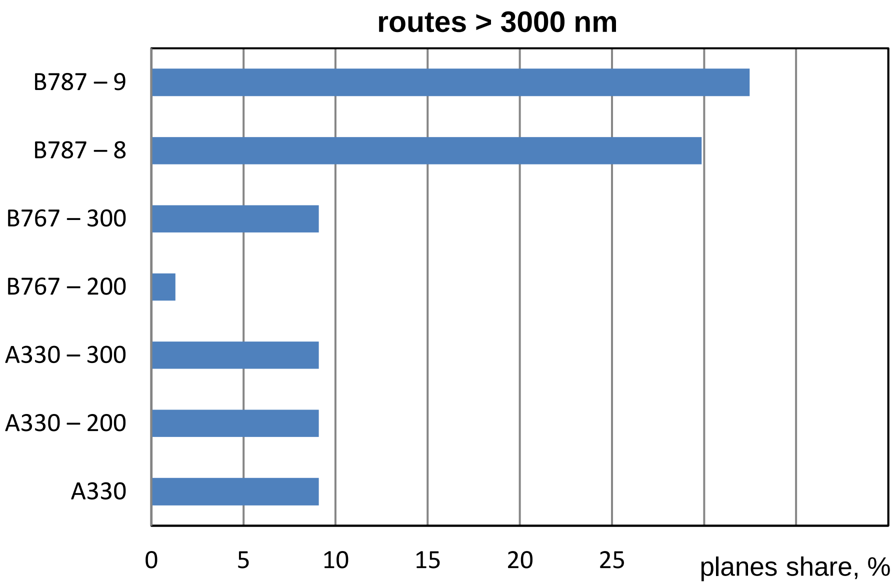


Figure 85. The distribution of aircraft types in the selected air routes range

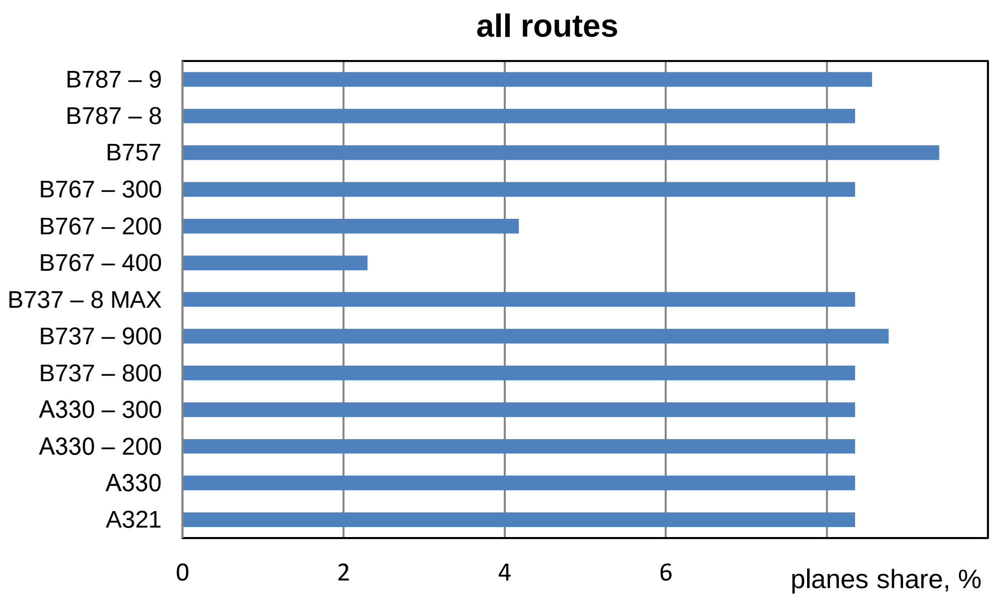


Figure 86. The distribution of aircraft types by overall air routes range

Also, the result of statistical data processing is the distribution of aircraft of the Boeing and Airbus companies. The relative share (percentage) of aircraft flying the routes of a different range is presented in Figure 87.

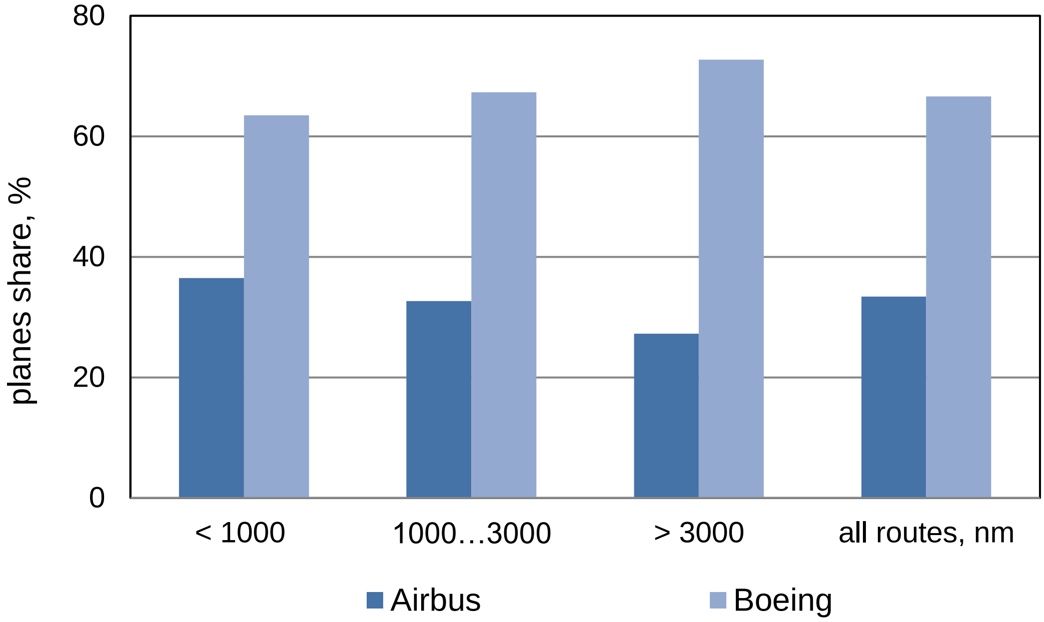


Figure 87. The distribution of airplanes by routes of different range for Airbus and Boeing

AV.3 Conclusions

Bringing new aircraft into service allows expanding the air routes. As new aircraft arrive and the airlines study their properties, the number of new routes continues to grow, as shown by the example of the Boeing 787 Dreamliner.

The B757 can continue to be used for the needs of the transatlantic market. At the same time, this aircraft affects significantly domestic traffic on short-haul and medium-haul routes, as evidenced by the data in Fig. 10 and Fig. 11. The continuing growth of low-cost airlines in both the primary and secondary markets also redirects in some ways the B757 back to its main operations, transatlantic flights. The result will be as follows: the aircraft will retain its crucial role in the aviation market and will also encourage the growth of airlines and airports.

Data analysis in Fig. 10-12 shows that the most common aircraft on short-haul routes are the B757, B737, A321. On routes from 1,000 to 3,000 nautical miles, the most common is the B737 and A330 families. On long-haul routes, over 3,000 nautical miles, B787 dominates. In general, for the sampled information, the distribution of the aircraft is quite equal, except for the B767-400 and -200. However, at the same time, Boeing airplanes dominate in all of the route ranges as shown in Fig. 14.

The analysis of statistical data allows concluding that a greater number of Boeing aircraft was caused by the prevalence in the aircraft supply in the 1990s and by the fact that these aircraft are in the fleet of different companies. To identify the trends in changing aircraft types flying various routes, it is reasonable to make periodic studies based on statistical data.

It should also be noted that airliners will not always strive to buy new aircraft, especially in the budget segment. Cheaper, outdated aircraft will be considered, as shown by the example of

B757. This, in turn, will make a negative impact on the reduction of harmful emissions from air transport, which is contrary to the objectives of ACARE Flightpath 2050.

AV.4 Routes tables

The following routes were considered for the A321 aircraft:

Airborne Airbus A321 (twinjet) (A321) Aircraft					Range	
№	Ident	Type	Origin	Destination	miles	nm
distance less than 1000 nm						
1	DLH1124	A321	Frankfurt Int'l (FRA / EDDF)	Barcelona Int'l (BCN / LEBL)	679	590
2	DLH45	A321	Tegel Int'l (TXL / EDDT)	Frankfurt Int'l (FRA / EDDF)	269	234
3	DLH93	A321	Munich Int'l (MUC / EDDM)	Frankfurt Int'l (FRA / EDDF)	186	162
4	AFR1138	A321	Charles de Gaulle/Roissy (CDG / LFPG)	Vienna Int'l (Schwechat) (VIE / LOWW)	644	560
5	THY2311	A321	İzmir Adnan Menderes Int'l (ADB / LTBJ)	Istanbul Ataturk Int'l (IST / LTBA)	206	179
6	HVN1270	A321	Tan Son Nhat Int'l (SGN / VVTS)	Tho Xuan (THD / VVTX)	633	550
7	AIC818	A321	Nanded (NDC / VAND)	Chandigarh (Chandigarh Air Force Base) (IXC / VICG)	795	691
8	AAL786	A321	Dallas-Fort Worth Intl (KDFW)	Chicago O'Hare Intl (KORD)	802	697
9	THY2123	A321	Ankara Esenboğa Havalimanı Int'l (ESB / LTAC)	Istanbul Ataturk Int'l (IST / LTBA)	227	197
10	CSN3600	A321	Nanjing Lukou Int'l (NKG / ZSNJ)	Guangzhou Baiyun Int'l (CAN / ZGGG)	671	583
11	ANA385	A321	Tokyo Int'l (Haneda) (HND / RJTT)	Miho Airfield (Yonago) (YGJ / RJOH)	368	320
12	DLH1181	A321	Porto / Oporto (OPO / LPPR)	Frankfurt Int'l (FRA / EDDF)	1026	892
13	HVN124	A321	Tan Son Nhat Int'l (SGN / VVTS)	Da Nang Int'l (DAD / VVDN)	376	327

Airborne Airbus A321 (twinjet) (A321) Aircraft					Range	
№	Ident	Type	Origin	Destination	miles	nm
14	AFR6105	A321	Toulouse-Blagnac (TLS / LFBO)	Paris Orly (ORY / LFPO)	356	309
15	THY1638	A321	Munich Int'l (MUC / EDDM)	Istanbul Ataturk Int'l (IST / LTBA)	978	850
16	CCA1561	A321	Beijing Capital Int'l (PEK / ZBAA)	Nanjing Lukou Int'l (NKG / ZSNJ)	590	513
17	THY2505	A321	Milas-Bodrum (BJV / LTFE)	Istanbul Ataturk Int'l (IST / LTBA)	265	230
18	VLG2115	A321	Barcelona Int'l (BCN / LEBL)	Malaga (AGP / LEMG)	476	414
19	EVA855	A321	Taiwan Taoyuan Int'l (TPE / RCTP)	Hong Kong Int'l (HKG / VHHH)	502	436
20	AFR6104	A321	Paris Orly (ORY / LFPO)	Toulouse-Blagnac (TLS / LFBO)	356	309
21	THY1721	A321	Istanbul Ataturk Int'l (IST / LTBA)	Tegel Int'l (TXL / EDDT)	1083	941
22	DLH243	A321	Leonardo da Vinci Int'l (Fiumicino Int'l) (FCO / LIRF)	Frankfurt Int'l (FRA / EDDF)	596	518
23	DLH2030	A321	Munich Int'l (MUC / EDDM)	Tegel Int'l (TXL / EDDT)	298	259
24	CES5666	A321	Xiamen Gaoqi Int'l (XMN / ZSAM)	Shanghai Hongqiao Int'l (SHA / ZSSS)	501	435
25	PAL330	A321	Manila Int'l (MNL / RPLL)	Xiamen Gaoqi Int'l (XMN / ZSAM)	719	625
26	CSC8813	A321	Chengdu Shuangliu Int'l (CTU / ZUUU)	Xuzhou (XUZ / ZSXZ)	812	706
27	WZZ2815	A321	Vienna Int'l (Schwechat) (VIE / LOWW)	Leonardo da Vinci Int'l (Fiumicino Int'l) (FCO / LIRF)	484	421

Airborne Airbus A321 (twinjet) (A321) Aircraft					Range	
№	Ident	Type	Origin	Destination	miles	nm
28	HVN1825	A321	Tan Son Nhat Int'l (SGN / VVTS)	Duong Dong (PQC / VVPQ)	186	162
29	EVA156	A321	Taipei Songshan (TSA / RCSS)	Gimpo Int'l (GMP / RKSS)	917	797
30	THY2134	A321	Istanbul Ataturk Int'l (IST / LTBA)	Ankara Esenboğa Havalimanı Int'l (ESB / LTAC)	227	197
Range from 1000 nm to 3000 nm						
1	PAL425	A321	Fukuoka (FUK / RJFF)	Manila Int'l (MNL / RPLL)	1447	1257
2	CSN3143	A321	Guangzhou Baiyun Int'l (CAN / ZGGG)	Tianjin Binhai Int'l (TSN / ZBTJ)	1114	968
3	HKE650	A321	Hong Kong Int'l (HKG / VHHH)	Narita Int'l (NRT / RJAA)	1842	1601
4	DLH1453	A321	Domodedovo Int'l (DME / UUDD)	Frankfurt Int'l (FRA / EDDF)	1275	1108
5	THY1993	A321	Istanbul Ataturk Int'l (IST / LTBA)	Manchester (MAN / EGCC)	1676	1456
6	THY5262	A321	İzmir Adnan Menderes Int'l (ADB / LTBJ)	King Abdulaziz Int'l (JED / OEJN)	1352	1175
7	AAL1658	A321	Phoenix Sky Harbor Intl (KPHX)	Philadelphia Intl (KPHL)	2074	1802
8	CBJ5765	A321	Changsha Huanghua Int'l (CSX / ZGHA)	Changchun Longjia Int'l (CGQ / ZYCC)	1293	1124
9	AAL803	A321	San Francisco Intl (KSFO)	Philadelphia Intl (KPHL)	2518	2188
10	PAL438	A321	Manila Int'l (MNL / RPLL)	Chubu Centrair Int'l (Centrair) (NGO / RJGG)	1717	1492

The following routes were considered for the A330 aircraft:

A330						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	THA110	A330	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	Chiang Mai Int'l (CNX / VTCC)	372	323
2	CCA1521	A330	Beijing Capital Int'l (PEK / ZBAA)	Shanghai Hongqiao Int'l (SHA / ZSSS)	670	582
3	TBA9821	A330	Chengdu Shuangliu Int'l (CTU / ZUUU)	Sanya Phoenix Int'l (SYX / ZJSY)	916	796
4	SVA1024	A330	King Abdulaziz Int'l (JED / OEJN)	King Khalid Int'l (RUH / OERK)	529	460
5	CCA4108	A330	Beijing Capital Int'l (PEK / ZBAA)	Chengdu Shuangliu Int'l (CTU / ZUUU)	968	841
6	CCA4420	A330	Chongqing Jiangbei Int'l (CKG / ZUCK)	Lhasa Gonggar (LXA / ZULS)	947	823
7	MSR661	A330	Cairo Int'l (CAI / HECA)	King Abdulaziz Int'l (JED / OEJN)	757	658
8	CSC8887	A330	Chengdu Shuangliu Int'l (CTU / ZUUU)	Beijing Capital Int'l (PEK / ZBAA)	968	841
9	SVA306	A330	Cairo Int'l (CAI / HECA)	King Abdulaziz Int'l (JED / OEJN)	757	658
10	SVA1110	A330	King Abdulaziz Int'l (JED / OEJN)	King Fahd Int'l (DMM / OEDF)	749	651
11	CCA4130	A330	Beijing Capital Int'l (PEK / ZBAA)	Chongqing Jiangbei Int'l (CKG / ZUCK)	910	791
12	TBA9847	A330	Chengdu Shuangliu Int'l (CTU / ZUUU)	Shenzhen Bao'an Int'l (SZX / ZGSZ)	821	713
13	CCA1373	A330	Beijing Capital Int'l (PEK / ZBAA)	Changsha Huanghua Int'l (CSX / ZGHA)	845	734

A330						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
14	CBJ5163	A330	Sanya Phoenix Int'l (SYX / ZJSY)	Hangzhou Xiaoshan Int'l (HGH / ZSHC)	1077	936
Routes with more than 1000 nm and less than 3000 nm range						
1	SVA257	A330	King Abdulaziz Int'l (JED / OEJN)	Istanbul Ataturk Int'l (IST / LTBA)	1465	1273
2	PAL421	A330	Tokyo Int'l (Haneda) (HND / RJTT)	Manila Int'l (MNL / RPLL)	1863	1619
3	CCA471	A330	Chengdu Shuangliu Int'l (CTU / ZUUU)	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	1186	1031
4	CSZ9605	A330	Shenzhen Bao'an Int'l (SZX / ZGSZ)	Shenyang Taoxian Int'l (SHE / ZYTX)	1429	1242
5	CCA909	A330	Beijing Capital Int'l (PEK / ZBAA)	Sheremetyevo Int'l (SVO / UUEE)	3605	3133
6	CSZ9622	A330	Harbin Taiping Int'l (HRB / ZYHB)	Shenzhen Bao'an Int'l (SZX / ZGSZ)	1738	1510
7	CEB805	A330	Manila Int'l (MNL / RPLL)	Singapore Changi (SIN / WSSS)	1478	1284
8	CCA926	A330	Narita Int'l (NRT / RJAA)	Beijing Capital Int'l (PEK / ZBAA)	1328	1154
9	SVA271	A330	King Abdulaziz Int'l (JED / OEJN)	Ankara Esenboğa Havalimanı Int'l (ESB / LTAC)	1327	1153
10	SVA741	A330	Chatrapati Shivaji Int'l (BOM / VABB)	King Khalid Int'l (RUH / OERK)	1724	1498
11	CSC8963	A330	Chengdu Shuangliu Int'l (CTU / ZUUU)	Shanghai Pudong Int'l (PVG / ZSPD)	1296	1126
12	RNA409	A330	Tribhuvan Int'l (KTM / VNKT)	Hong Kong Int'l (HKG / VHHH)	1824	1585

A330						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
13	CEB5055	A330	Narita Int'l (NRT / RJAA)	Manila Int'l (MNL / RPLL)	1898	1649
14	CSZ9155	A330	Beijing Capital Int'l (PEK / ZBAA)	Sanya Phoenix Int'l (SYX / ZJSY)	1566	1361
15	CCA1362	A330	Haikou Meilan Int'l (HAK / ZJHK)	Beijing Capital Int'l (PEK / ZBAA)	1440	1251
16	CCA1404	A330	Kunming Changshui Int'l (KMG / ZPPP)	Beijing Capital Int'l (PEK / ZBAA)	1303	1132
17	IRA711	A330	Imam Khomeini Int'l (IKA / OIIE)	London Heathrow (LHR / EGLL)	2750	2390
18	CCA1352	A330	Guangzhou Baiyun Int'l (CAN / ZGGG)	Beijing Capital Int'l (PEK / ZBAA)	1170	1017
19	SVA259	A330	Prince Mohammad Bin Abdulaziz (MED / OEMA)	Istanbul Ataturk Int'l (IST / LTBA)	1298	1128
Routes with more than 3000 nm range						
1	CCA911	A330	Beijing Capital Int'l (PEK / ZBAA)	Stockholm-Arlanda (ARN / ESSA)	4162	3617
2	CSZ9067	A330	Shenzhen Bao'an Int'l (SZX / ZGSZ)	London Heathrow (LHR / EGLL)	5968	5186
3	CSC8501	A330	Zhengzhou Xinzheng Int'l (CGO / ZHCC)	Vancouver Int'l (CYVR)	5687	4942
4	CCA855	A330	Beijing Capital Int'l (PEK / ZBAA)	London Heathrow (LHR / EGLL)	5071	4407
5	AZA787	A330	Narita Int'l (NRT / RJAA)	Malpensa Int'l (MXP / LIMC)	6065	5270
6	LNI104	A330	Sultan Hasanuddin Int'l (UPG / WAAA)	King Abdulaziz Int'l (JED / OEJN)	5741	4989

A330						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
7	GIA974	A330	Sultan Iskandarmuda (Blang Bintang) (BTJ / WITT)	Prince Mohammad Bin Abdulaziz (MED / OEMA)	3917	3404

The following routes were considered for the A330-200 aircraft:

A330-200						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	KAC541	A332	Kuwait Int'l (KWI / OKBK)	Cairo Int'l (CAI / HECA)	997	866
2	MEA364	A332	Beirut Air Base/Rafic Hariri Int'l (Beirut Int'l) (BEY / OLBA)	King Abdulaziz Int'l (JED / OEJN)	869	755
3	THY413	A332	Istanbul Ataturk Int'l (IST / LTBA)	Vnukovo (VKO / UUWW)	1082	940
4	QFA455	A332	Sydney (SYD / YSSY)	Melbourne Tullamarine (MEL / YMML)	438	381
5	CSN3095	A332	Shanghai Pudong Int'l (PVG / ZSPD)	Taiwan Taoyuan Int'l (TPE / RCTP)	421	366
6	THY1907	A332	Istanbul Ataturk Int'l (IST / LTBA)	Zurich (Kloten) (ZRH / LSZH)	1097	953
7	MEA424	A332	Beirut Air Base/Rafic Hariri Int'l (Beirut Int'l) (BEY / OLBA)	King Khalid Int'l (RUH / OERK)	911	792
8	CCA1430	A332	Chongqing Jiangbei Int'l (CKG / ZUCK)	Beijing Capital Int'l (PEK / ZBAA)	910	791
9	DAH1002	A332	Houari Boumedienne (ALG / DAAG)	Charles de Gaulle/Roissy (CDG / LFPG)	853	741
10	CES2158	A332	Shanghai Hongqiao Int'l (SHA / ZSSS)	Xi'an Xianyang Int'l (XIY / ZLXY)	764	664
11	AEA1091	A332	Barajas Int'l (MAD / LEMD)	Amsterdam Schiphol (AMS / EHAM)	907	788

A330-200						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
12	THY805	A332	Erbil Int'l (EBL / ORER)	Istanbul Ataturk Int'l (IST / LTBA)	880	765
13	CES5222	A332	Chengdu Shuangliu Int'l (CTU / ZUUU)	Shanghai Pudong Int'l (PVG / ZSPD)	1059	920
14	CHH7341	A332	Shenzhen Bao'an Int'l (SZX / ZGSZ)	Guiyang Longdongbao (KWE / ZUGY)	517	449
15	CSN3571	A332	Guangzhou Baiyun Int'l (CAN / ZGGG)	Shanghai Hongqiao Int'l (SHA / ZSSS)	732	636
Routes with more than 1000 nm and less than 3000 nm range						
1	CSN3162	A332	Beijing Capital Int'l (PEK / ZBAA)	Guangzhou Baiyun Int'l (CAN / ZGGG)	1170	1017
2	KAL941	A332	Incheon Int'l (ICN / RKSI)	Tashkent (TAS / UTTT)	3013	2618
3	MAS377	A332	Guangzhou Baiyun Int'l (CAN / ZGGG)	Kuala Lumpur Int'l (KUL / WMKK)	1625	1412
4	ALK315	A332	Kuala Lumpur Int'l (KUL / WMKK)	Bandaranaike Int'l (CMB / VCBI)	1536	1335
5	QTR638	A332	Hamad Int'l (DOH / OTHH)	Shahjalal International Airport (DAC / VGHS)	2434	2115
6	CRK629	A332	Incheon Int'l (ICN / RKSI)	Hong Kong Int'l (HKG / VHHH)	1288	1119
7	CES565	A332	Shanghai Pudong Int'l (PVG / ZSPD)	Singapore Changi (SIN / WSSS)	2367	2057
8	PAL468	A332	Manila Int'l (MNL / RPLL)	Incheon Int'l (ICN / RKSI)	1623	1410
9	QTR8628	A332	Hamad Int'l (DOH / OTHH)	Bengaluru Int'l (BLR / VOBL)	1893	1645
10	CSN3120	A332	Beijing Capital Int'l (PEK / ZBAA)	Haikou Meilan Int'l (HAK / ZJHK)	1440	1251

A330-200						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
11	QFA158	A332	Auckland (AKL / NZAA)	Melbourne Tullamarine (MEL / YMML)	1641	1426
12	TPA4016	A332	Jose Maria Cordova Int'l (MDE / SKRG)	Miami Intl (KMIA)	1458	1267
13	CSN3109	A332	Guangzhou Baiyun Int'l (CAN / ZGGG)	Beijing Capital Int'l (PEK / ZBAA)	1170	1017
14	QTR1399	A332	Hamad Int'l (DOH / OTHH)	Tunis-Carthage Int'l (TUN / DTTA)	2557	2222
15	KAC165	A332	Kuwait Int'l (KWI / OKBK)	Leonardo da Vinci Int'l (Fiumicino Int'l) (FCO / LIRF)	2172	1887
16	QTR8271	A332	Hamad Int'l (DOH / OTHH)	Zaragoza (ZAZ / LEZG)	3188	2770
17	CHH7246	A332	Urumqi Diwopu Int'l (URC / ZWWW)	Beijing Capital Int'l (PEK / ZBAA)	1512	1314
18	MEA211	A332	Beirut Air Base/Rafic Hariri Int'l (Beirut Int'l) (BEY / OLBA)	Charles de Gaulle/Roissy (CDG / LFPG)	1983	1723
Routes with more than 3000 nm range						
1	CES767	A332	Qingdao Liuting Int'l (TAO / ZSQD)	San Francisco Intl (KSFO)	6360	5527
2	THY601	A332	Lusaka International Airport (LUN / FLKK)	Istanbul Ataturk Int'l (IST / LTBA)	3895	3385
3	CES7053	A332	Hangzhou Xiaoshan Int'l (HGH / ZSHC)	Male Int'l (MLE / VRMM)	3547	3082
4	CES581	A332	Shanghai Pudong Int'l (PVG / ZSPD)	Vancouver Int'l (CYVR)	5848	5082
5	CES2855	A332	Nanjing Lukou Int'l (NKG / ZSNJ)	Los Angeles Intl (KLAX)	6851	5953
6	AFR355	A332	Seattle-Tacoma Intl (KSEA)	Charles de Gaulle/Roissy (CDG / LFPG)	5193	4513

A330-200						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
7	FJI811	A332	Los Angeles Intl (KLAX)	Nadi Int'l (NAN / NFFN)	5597	4864

The following routes were considered for the A330-300 aircraft:

A330-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	CCA196	A333	Taiwan Taoyuan Int'l (TPE / RCTP)	Shanghai Pudong Int'l (PVG / ZSPD)	421	366
2	CES5115	A333	Shanghai Hongqiao Int'l (SHA / ZSSS)	Beijing Capital Int'l (PEK / ZBAA)	670	582
3	HDA951	A333	Qingdao Liuting Int'l (TAO / ZSQD)	Hong Kong Int'l (HKG / VHHH)	1040	904
4	CSH845	A333	Shanghai Hongqiao Int'l (SHA / ZSSS)	Hong Kong Int'l (HKG / VHHH)	766	666
5	KAL862	A333	Qingdao Liuting Int'l (TAO / ZSQD)	Incheon Int'l (ICN / RKSI)	346	301
6	CCA4109	A333	Chengdu Shuangliu Int'l (CTU / ZUUU)	Beijing Capital Int'l (PEK / ZBAA)	968	841
7	CSN3538	A333	Shanghai Hongqiao Int'l (SHA / ZSSS)	Guangzhou Baiyun Int'l (CAN / ZGGG)	732	636
8	HDA437	A333	Kaohsiung Int'l (KHH / RCKH)	Hong Kong Int'l (HKG / VHHH)	412	358
9	AAR360	A333	Hangzhou Xiaoshan Int'l (HGH / ZSHC)	Incheon Int'l (ICN / RKSI)	609	529
10	CPA467	A333	Taiwan Taoyuan Int'l (TPE / RCTP)	Hong Kong Int'l (HKG / VHHH)	502	436

A330-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
11	AAR1045	A333	Gimpo Int'l (GMP / RKSS)	Tokyo Int'l (Haneda) (HND / RJTT)	734	638
12	MAS782	A333	Kuala Lumpur Int'l (KUL / WMKK)	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	760	660
13	KAL870	A333	Dalian Zhoushuizi Int'l (DLC / ZYTL)	Incheon Int'l (ICN / RKSI)	287	249
14	KAL1225	A333	Gimpo Int'l (GMP / RKSS)	Jeju Int'l (CJU / RKPC)	281	244
15	CBJ5128	A333	Kunming Changshui Int'l (KMG / ZPPP)	Hangzhou Xiaoshan Int'l (HGH / ZSHC)	1128	980
16	CES5113	A333	Shanghai Hongqiao Int'l (SHA / ZSSS)	Beijing Capital Int'l (PEK / ZBAA)	670	582
17	CRK254	A333	Hong Kong Int'l (HKG / VHHH)	Taiwan Taoyuan Int'l (TPE / RCTP)	502	436
Routes with more than 1000 nm and less than 3000 nm range						
1	XAX318	A333	Kuala Lumpur Int'l (KUL / WMKK)	Tianjin Binhai Int'l (TSN / ZBTJ)	2702	2348
2	AAR372	A333	Shenzhen Bao'an Int'l (SZX / ZGSZ)	Incheon Int'l (ICN / RKSI)	1272	1105
3	XAX502	A333	Jeju Int'l (CJU / RKPC)	Kuala Lumpur Int'l (KUL / WMKK)	2663	2314
4	CSN3059	A333	Guangzhou Baiyun Int'l (CAN / ZGGG)	Bandaranaike Int'l (CMB / VCBI)	2487	2161
5	VKG1728	A333	Stockholm-Arlanda (ARN / ESSA)	Tenerife South (Reina Sofia) (TFS / GCTS)	2722	2365
6	CAL108	A333	Taiwan Taoyuan Int'l (TPE / RCTP)	Narita Int'l (NRT / RJAA)	1357	1179
7	PAL408	A333	Manila Int'l (MNL / RPLL)	Kansai Int'l (KIX / RJBB)	1639	1424

A330-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
8	XAX522	A333	Kuala Lumpur Int'l (KUL / WMKK)	Tokyo Int'l (Haneda) (HND / RJTT)	3328	2892
9	CAL751	A333	Taiwan Taoyuan Int'l (TPE / RCTP)	Singapore Changi (SIN / WSSS)	2005	1742
10	SIA602	A333	Singapore Changi (SIN / WSSS)	Incheon Int'l (ICN / RKSI)	2878	2501
11	CCA112	A333	Hong Kong Int'l (HKG / VHHH)	Beijing Capital Int'l (PEK / ZBAA)	1239	1077
12	THY1587	A333	Istanbul Ataturk Int'l (IST / LTBA)	Frankfurt Int'l (FRA / EDDF)	1160	1008
13	MAS73	A333	Hong Kong Int'l (HKG / VHHH)	Kuala Lumpur Int'l (KUL / WMKK)	1582	1375
14	QTR653	A333	Tribhuvan Int'l (KTM / VNKT)	Hamad Int'l (DOH / OTHH)	2090	1816
15	CRK697	A333	New Chitose (CTS / RJCC)	Hong Kong Int'l (HKG / VHHH)	2134	1854
16	AFL2550	A333	Sheremetyevo Int'l (SVO / UUEE)	Amsterdam Schiphol (AMS / EHAM)	1334	1159
17	AAR751	A333	Incheon Int'l (ICN / RKSI)	Singapore Changi (SIN / WSSS)	2878	2501
18	HDA381	A333	Fukuoka (FUK / RJFF)	Hong Kong Int'l (HKG / VHHH)	1274	1107
19	CES5378	A333	Sanya Phoenix Int'l (SYX / ZJSY)	Shanghai Pudong Int'l (PVG / ZSPD)	1178	1024
Routes with more than 3000 nm range						
1	MAS150	A333	Kuala Lumpur Int'l (KUL / WMKK)	King Abdulaziz Int'l (JED / OEJN)	4396	3820
2	QFA37	A333	Melbourne Tullamarine (MEL / YMML)	Singapore Changi (SIN / WSSS)	3754	3262

A330-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
3	ALK503	A333	Bandaranaike Int'l (CMB / VCBI)	London Heathrow (LHR / EGLL)	5421	4711
4	MAS158	A333	Kuala Lumpur Int'l (KUL / WMKK)	Prince Mohammad Bin Abdulaziz (MED / OEMA)	4391	3816

The following routes were considered for the B737-800 aircraft:

Boeing 737-800						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	CXA8492	B738	Chongqing Jiangbei Int'l (CKG / ZUCK)	Xiamen Gaoqi Int'l (XMN / ZSAM)	792	688
2	CXA8317	B738	Shanghai Hongqiao Int'l (SHA / ZSSS)	Shenzhen Bao'an Int'l (SZX / ZGSZ)	751	653
3	VOZ974	B738	Brisbane (BNE / YBBN)	Sydney (SYD / YSSY)	484	421
4	CHH7725	B738	Tianjin Binhai Int'l (TSN / ZBTJ)	Harbin Taiping Int'l (HRB / ZYHB)	639	555
5	UBG203	B738	Shah Amanat Int'l (M.A. Hannan Int'l) (CGP / VGEG)	Netaji Subhash Chandra Bose Int'l (CCU / VECC)	217	189
6	ESR703	B738	Cheongju (CJJ / RKTU)	Jeju Int'l (CJU / RKPC)	229	199
7	MAS789	B738	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	Kuala Lumpur Int'l (KUL / WMKK)	760	660
8	CSZ9239	B738	Shenzhen Bao'an Int'l (SZX / ZGSZ)	Lanzhou Zhongchuan International (LHW / ZLLL)	1137	988
9	GLO1785	B738	Foz do Iguacu Int'l (Cataratas Int'l) (IGU / SBFI)	Afonso Pena Int'l (CWB / SBCT)	331	288

Boeing 737-800						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
10	FZA6636	B738	Zhengzhou Xinzheng Int'l (CGO / ZHCC)	Ningbo Lishe Int'l (NGB / ZSNB)	551	479
11	CAW6324	B738	Port Elizabeth (PLZ / FAPE)	Cape Town Int'l (CPT / FACT)	403	350
12	CXA8442	B738	Chengdu Shuangliu Int'l (CTU / ZUUU)	Xiamen Gaoqi Int'l (XMN / ZSAM)	963	837
13	RYR9615	B738	Ciampino (Giovan Battista Pastine) (CIA / LIRA)	Eindhoven (EIN / EHEH)	749	651
14	CCA1481	B738	Tianjin Binhai Int'l (TSN / ZBTJ)	Guilin Liangjiang Int'l (KWL / ZGKL)	1052	914
15	RYR1260	B738	Athens Int'l, Eleftherios Venizelos (ATH / LGAV)	Orio al Serio Int'l (BGY / LIME)	907	788
16	SAS4104	B738	Oslo, Gardermoen (OSL / ENGM)	Bodo (BOO / ENBO)	499	434
17	ASA180	B738	Anchorage Intl (PANC)	Juneau Intl (JNU / PAJN)	595	517
18	MSR681	B738	Cairo Int'l (CAI / HECA)	King Fahd Int'l (DMM / OEDF)	1147	997
19	LNI635	B738	Fatmawati Soekarno (BKS / WIGG)	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	336	292
20	JAI837	B738	Indira Gandhi Int'l (DEL / VIDP)	Udaipur (UDR / VAUD)	337	293
21	JYH1039	B738	Nanjing Lukou Int'l (NKG / ZSNJ)	Harbin Taiping Int'l (HRB / ZYHB)	1039	903
22	QFA694	B738	Adelaide Int'l (ADL / YPAD)	Melbourne Tullamarine (MEL / YMML)	399	347
23	JNA322	B738	Jeju Int'l (CJU / RKPC)	Gimpo Int'l (GMP / RKSS)	281	244
24	GLP1026	B738	Adler-Sochi Int'l (AER / URSS)	Domodedovo Int'l (DME / UUDD)	832	723
25	AFL1134	B738	Sheremetyevo Int'l (SVO / UUEE)	Adler-Sochi Int'l (AER / URSS)	873	759

Boeing 737-800						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
26	JAL840	B738	Tianjin Binhai Int'l (TSN / ZBTJ)	Chubu Centrair Int'l (Centrair) (NGO / RJGG)	1113	967
27	CSN3138	B738	Beijing Capital Int'l (PEK / ZBAA)	Wuhan Tianhe (WUH / ZHHH)	657	571
28	CES2465	B738	Wuhan Tianhe (WUH / ZHHH)	Shantou (SWA / ZGOW)	533	463
Routes with more than 1000 nm and less than 3000 nm range						
1	JNA61	B738	Incheon Int'l (ICN / RKSI)	Kota Kinabalu Int'l (BKI / WBKK)	2277	1979
2	PGT939	B738	Istanbul Sabiha Gokcen Int'l (SAW / LTFJ)	Basle-Mulhouse (BSL / LFSB)	1169	1016
3	RYR5158	B738	Malaga (AGP / LEMG)	Newcastle (NCL / EGNT)	1277	1110
4	RYR3208	B738	Manchester (MAN / EGCC)	Malaga (AGP / LEMG)	1159	1007
5	MSR845	B738	Cairo Int'l (CAI / HECA)	Houari Boumedienne (ALG / DAAG)	1684	1463
6	AMX684	B738	Lic. Benito Juarez Int'l (MEX / MMMX)	Mariscal Sucre Int'l (UIO / SEQM)	1954	1698
7	MAS853	B738	Kuala Lumpur Int'l (KUL / WMKK)	Ngurah Rai/Bali Intl (DPS / WADD)	1222	1062
8	AMX692	B738	Lic. Benito Juarez Int'l (MEX / MMMX)	Toronto Pearson Int'l (CYYZ)	2140	1860
9	CAL732	B738	Penang Int'l (PEN / WMKP)	Taiwan Taoyuan Int'l (TPE / RCTP)	1951	1695
10	AFL2607	B738	Lisbon / Lisboa,Portela (Lisbon) (LIS / LPPT)	Sheremetyevo Int'l (SVO / UUEE)	2421	2104
11	CDG8450	B738	Nanning Wuxu Int'l (NNG / ZGNN)	Hohhot Baita Int'l (HET / ZBHH)	1280	1112
12	GLO1741	B738	Eduardo Gomes Int'l (MAO / SBEG)	Presidente Juscelino Kubitschek Int'l (BSB / SBBR)	1212	1053

The following routes were considered for the B737-900 aircraft:

Boeing 737-900						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	LNI261	B739	Sepinggan Int'l (BPN / WALL)	Juanda Int'l (SUB / WARR)	509	442
2	THY2247	B739	Sanliurfa (GNY / LTCS)	Istanbul Ataturk Int'l (IST / LTBA)	602	523
3	KAL1118	B739	Gimhae Int'l (PUS / RKPK)	Gimpo Int'l (GMP / RKSS)	204	177
4	LNI768	B739	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	Sepinggan Int'l (BPN / WALL)	783	680
5	TLM807	B739	Krabi (KBV / VTSG)	Don Muang Int'l (Old Bangkok Int'l) (DMK / VTBD)	417	362
6	LNI666	B739	Juanda Int'l (SUB / WARR)	Temindung (SRI / WALS)	564	490
7	KAL848	B739	Jinan Yaoqiang (TNA / ZSJN)	Incheon Int'l (ICN / RKSI)	511	444
8	LNI649	B739	Lombok International (LOP / WADL)	Juanda Int'l (SUB / WARR)	258	224
9	LNI973	B739	Hang Nadim (BTH / WIDD)	Kuala Namu International (KNO / WIMM)	402	349
10	OMA634	B739	Abu Dhabi Int'l (AUH / OMAA)	Seeb Int'l (MCT / OOMS)	237	206
11	KAL1931	B739	Yeosu (RSU / RKJY)	Jeju Int'l (CJU / RKPC)	112	97
12	BTK6513	B739	Ngurah Rai/Bali Intl (DPS / WADD)	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	611	531
13	OMA670	B739	Hamad Int'l (DOH / OTHH)	Seeb Int'l (MCT / OOMS)	436	379
14	OKA2718	B739	Jeju Int'l (CJU / RKPC)	Tianjin Binhai Int'l (TSN / ZBTJ)	640	556
15	LNI925	B739	El Tari (Eltari) (KOE / WATT)	Ngurah Rai/Bali Intl (DPS / WADD)	588	511
16	TLM740	B739	Don Muang Int'l (Old Bangkok Int'l) (DMK / VTBD)	Surat Thani (URT / VTSB)	345	300

Boeing 737-900						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
17	CSZ9133	B739	Shenzhen Bao'an Int'l (SZX / ZGSZ)	Taiyuan Wusu (TYN / ZBYN)	1047	910
18	LNI598	B739	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	Juanda Int'l (SUB / WARR)	430	374
19	ESR219	B739	Gimpo Int'l (GMP / RKSS)	Jeju Int'l (CJU / RKPC)	281	244
20	LNI787	B739	Pattimura (AMQ / WAPP)	Sultan Hasanuddin Int'l (UPG / WAAA)	596	518
21	LNI316	B739	Juanda Int'l (SUB / WARR)	Syamsudin Noor (BDJ / WAOO)	305	265
22	BK2718	B739	Jeju Int'l (CJU / RKPC)	Tianjin Binhai Int'l (TSN / ZBTJ)	640	556
23	BTK6884	B739	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	Kuala Namu International (KNO / WIMM)	863	750
24	LNI603	B739	Sultan Thaha (DJB / WIJJ)	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	374	325
25	KAL1119	B739	Gimpo Int'l (GMP / RKSS)	Gimhae Int'l (PUS / RKPK)	204	177
26	TLM627	B739	Ubon Ratchathani (UBP / VTUU)	Don Muang Int'l (Old Bangkok Int'l) (DMK / VTBD)	300	261
27	LNI693	B739	El Tari (Eltari) (KOE / WATT)	Juanda Int'l (SUB / WARR)	769	668
Routes with more than 1000 nm and less than 3000 nm range						
1	CMP364	B739	Ministro Pistarini Int'l (EZE / SAEZ)	Tocumen Int'l (PTY / MPTO)	3329	2893
2	UAL366	B739	Los Angeles Intl (KLAX)	Washington Dulles Intl (KIAD)	2402	2087
3	LNI2741	B739	Sam Ratulangi Int'l (MDC / WAMM)	Guangzhou Baiyun Int'l (CAN / ZGGG)	1701	1478
4	UAL1724	B739	Ellison Onizuka Kona Intl At Keahole (KOA / PHKO)	San Francisco Intl (KSFO)	2534	2202
5	UAL1268	B739	Los Angeles Intl (KLAX)	Chicago O'Hare Intl (KORD)	1837	1596

Boeing 737-900						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
6	UAL308	B739	San Francisco Intl (KSFO)	Washington Dulles Intl (KIAD)	2498	2171
7	TLM935	B739	Changsha Huanghua Int'l (CSX / ZGHA)	Don Muang Int'l (Old Bangkok Int'l) (DMK / VTBD)	1277	1110
8	DAL1708	B739	McCarran Intl (KLAS)	Cincinnati/Northern Kentucky International Airport (KCVG)	1720	1495
9	DAL2775	B739	Seattle-Tacoma Intl (KSEA)	Hartsfield-Jackson Intl (KATL)	2247	1953
10	TLM977	B739	Zhengzhou Xinzheng Int'l (CGO / ZHCC)	Phuket Int'l (HKT / VTSP)	2076	1804
11	UAL1583	B739	McCarran Intl (KLAS)	Newark Liberty Intl (KEWR)	2305	2003
12	DAL2968	B739	Seattle-Tacoma Intl (KSEA)	John F Kennedy Intl (KJFK)	2418	2101
13	ASA378	B739	San Diego Intl (KSAN)	Baltimore/Washington Intl (KBWI)	2366	2056
14	TLM973	B739	Nanjing Lukou Int'l (NKG / ZSNJ)	Phuket Int'l (HKT / VTSP)	2102	1827
15	ASA676	B739	Seattle-Tacoma Intl (KSEA)	Tucson Intl (KTUS)	1247	1084

The following routes were considered for the B737-8 MAX aircraft:

Boeing 737-8 MAX						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	ACA230	B38M	Vancouver Int'l (CYVR)	Calgary Int'l (CYYC)	458	398
2	CCA1294	B38M	Hotan (HTN / ZWTN)	Urumqi Diwopu Int'l (URC / ZWWW)	620	539
3	CDG8007	B38M	Yinchuan Helanshan (INC / ZLIC)	Nanning Wuxu Int'l (NNG / ZGNN)	1092	949

Boeing 737-8 MAX						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
4	SEJ192	B38M	Indira Gandhi Int'l (DEL / VIDP)	Bagdogra (IXB / VEBD)	700	608
5	CSN363	B38M	Guangzhou Baiyun Int'l (CAN / ZGGG)	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	1061	922
6	JAI728	B38M	Lok Nayak Jaya Prakash Narayan (Patna) (PAT / VEPT)	Indira Gandhi Int'l (DEL / VIDP)	533	463
7	CDG1171	B38M	Jinan Yaoqiang (TNA / ZSJN)	Guangzhou Baiyun Int'l (CAN / ZGGG)	960	834
8	THY687	B38M	Mogadishu (MGQ / HCMM)	Djibouti-Ambouli Int'l (JIB / HDAM)	676	587
9	LNI797	B38M	Sultan Hasanuddin Int'l (UPG / WAAA)	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	891	774
10	CSN3535	B38M	Guangzhou Baiyun Int'l (CAN / ZGGG)	Nanchang Changbei Int'l (KHN / ZSCN)	412	358
11	LOT281	B38M	Warsaw Frederic Chopin (WAW / EPWA)	London Heathrow (LHR / EGLL)	914	794
12	SEJ8171	B38M	Indira Gandhi Int'l (DEL / VIDP)	Dabolim (Goa) / Dabolim Navy Airbase (GOI / VOGO)	983	854
13	CSN8287	B38M	Guangzhou Baiyun Int'l (CAN / ZGGG)	Lanzhou Zhongchuan International (LHW / ZLLL)	1076	935
Routes with more than 1000 nm and less than 3000 nm range						
1	LOT196	B38M	Astana Int'l (TSE / UACC)	Warsaw Frederic Chopin (WAW / EPWA)	2127	1848
2	ICE528	B38M	Keflavik Int'l (KEF / BIKF)	Tegel Int'l (TXL / EDDT)	1496	1300
3	ICE470	B38M	Keflavik Int'l (KEF / BIKF)	London Gatwick (LGW / EGKK)	1204	1046
4	WJA1857	B38M	Kahului (OGG / PHOG)	Calgary Int'l (CYYC)	3172	2756
5	WJA2244	B38M	Calgary Int'l (CYYC)	Lic. Gustavo Diaz Ordaz Int'l (PVR / MMPR)	2200	1912

Boeing 737-8 MAX						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
6	SLK411	B38M	Tribhuvan Int'l (KTM / VNKT)	Singapore Changi (SIN / WSSS)	2200	1912
7	WJA1119	B38M	McCarran Intl (KLAS)	Toronto Pearson Int'l (CYYZ)	2037	1770
8	NAX1939	B38M	Dubai Int'l (DXB / OMDB)	Copenhagen (CPH / EKCH)	2998	2605
9	CSN6943	B38M	Urumqi Diwopu Int'l (URC / ZWWW)	Chengdu Shuangliu Int'l (CTU / ZUUU)	1289	1120
10	CDG4938	B38M	Singapore Changi (SIN / WSSS)	Jinan Yaoqiang (TNA / ZSJN)	2597	2257
11	IBK366	B38M	Helsinki-Vantaa (HEL / EFHK)	London Gatwick (LGW / EGKK)	1157	1005
12	CSN6885	B38M	Urumqi Diwopu Int'l (URC / ZWWW)	Guangzhou Baiyun Int'l (CAN / ZGGG)	2039	1772
13	CSN3038	B38M	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	Guangzhou Baiyun Int'l (CAN / ZGGG)	2091	1817
14	ETH853	B38M	Bole Int'l (ADD / HAAB)	Ivato Int'l (TNR / FMMI)	2010	1747
15	SEJ55	B38M	Sri Guru Ram Dass Jee International Airport (ATQ / VIAR)	Dubai Int'l (DXB / OMDB)	1261	1096
16	SLK802	B38M	Darwin Int'l / RAAF (DRW / YPDN)	Singapore Changi (SIN / WSSS)	1639	1424
17	AAL2237	B38M	Los Angeles Intl (KLAX)	Miami Intl (KMIA)	2406	2091
18	AAL946	B38M	Mariscal Sucre Int'l (UIO / SEQM)	Miami Intl (KMIA)	1837	1596
19	ETH931	B38M	Bole Int'l (ADD / HAAB)	Akanu Ibiam Int'l (ENU / DNEN)	2147	1866
20	AMX48	B38M	Lic. Benito Juarez Int'l (MEX / MMMX)	Jorge Chavez Int'l (LIM / SPJC)	2641	2295
21	ACA588	B38M	Kahului (OGG / PHOG)	Calgary Int'l (CYYC)	3195	2776
22	JAF11M	B38M	Melsbroek Air Base (EBMB)	Tenerife South (Reina Sofia) (TFS / GCTS)	1925	1673

Boeing 737-8 MAX						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
23	MGL298	B38M	Hong Kong Int'l (HKG / VHHH)	Chinggis Khaan Int'l (ULN / ZMUB)	1810	1573
24	CSN354	B38M	Singapore Changi (SIN / WSSS)	Guangzhou Baiyun Int'l (CAN / ZGGG)	1648	1432
25	FJI915	B38M	Nadi Int'l (NAN / NFFN)	Sydney (SYD / YSSY)	1972	1714
26	CCA1270	B38M	Korla (KRL / ZWKL)	Beijing Capital Int'l (PEK / ZBAA)	1588	1380
27	CSN6965	B38M	Lanzhou Zhongchuan International (LHW / ZLLL)	Haikou Meilan Int'l (HAK / ZJHK)	1220	1060

The following routes were considered for the B767-300 aircraft:

Boeing 767-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	ADO87	B763	Tokyo Int'l (Haneda) (HND / RJTT)	Asahikawa (AKJ / RJEC)	579	503
2	ANA8492	B763	Dalian Zhoushuizi Int'l (DLC / ZYTL)	Kansai Int'l (KIX / RJBB)	822	714
3	JAL916	B763	Naha (OKA / ROAH)	Tokyo Int'l (Haneda) (HND / RJTT)	967	840
4	ETH908	B763	Blaise Diagne (DSS / GOBD)	Senou Int'l (BKO / GABS)	631	548
5	AAR8966	B763	Jeju Int'l (CJU / RKPC)	Gimpo Int'l (GMP / RKSS)	281	244
6	LAE1801	B763	Miami Intl (KMIA)	La Aurora Int'l (GUA / MGGT)	1064	925
7	JAL912	B763	Naha (OKA / ROAH)	Tokyo Int'l (Haneda) (HND / RJTT)	967	840

Boeing 767-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
8	AAR113	B763	Kansai Int'l (KIX / RJBB)	Incheon Int'l (ICN / RKSI)	535	465
9	CJT570	B763	Winnipeg Int'l (CYWG)	Montreal-Mirabel (CYMX)	1119	972
10	GTI3500	B763	Baltimore/Washington Intl (KBWI)	Minneapolis/St Paul Intl (KMSP)	936	813
11	AJX928	B763	Qingdao Liuting Int'l (TAO / ZSQD)	Narita Int'l (NRT / RJAA)	1119	972
12	CJT573	B763	Hamilton/John C. Munro Int'l (CYHM)	Winnipeg Int'l (CYWG)	995	865
13	CJT571	B763	Hamilton/John C. Munro Int'l (CYHM)	Winnipeg Int'l (CYWG)	1001	870
Routes with more than 1000 nm and less than 3000 nm range						
1	UZB604	B763	Vnukovo (VKO / UUWW)	Tashkent (TAS / UTTT)	1748	1519
2	UPS355	B763	El Dorado Int'l (BOG / SKBO)	Miami Intl (KMIA)	1514	1316
3	DAL181	B763	Narita Int'l (NRT / RJAA)	Manila Int'l (MNL / RPLL)	1898	1649
4	ATN308	B763	Paya Lebar Air Base (RSAF) (QPG / WSAP)	(FJDG)	2256	1960
5	ABX2203	B763	Los Angeles Intl (KLAX)	Lic. Benito Juarez Int'l (MEX / MMMX)	1555	1351
6	MAA6814	B763	Lic. Benito Juarez Int'l (MEX / MMMX)	Los Angeles Intl (KLAX)	1616	1404
7	UZB613	B763	Tashkent (TAS / UTTT)	Vnukovo (VKO / UUWW)	1748	1519
8	AJX831	B763	Narita Int'l (NRT / RJAA)	Tan Son Nhat Int'l (SGN / VVTS)	2727	2370
9	ACA158	B763	Calgary Int'l (CYYC)	Toronto Pearson Int'l (CYYZ)	1693	1471
10	CJT572	B763	Calgary Int'l (CYYC)	Hamilton/John C. Munro Int'l (CYHM)	1678	1458

Boeing 767-300						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
11	UPS2968	B763	Ontario Intl (KONT)	Kahului (OGG / PHOG)	2615	2272
12	JAL8944	B763	Guam Intl (PGUM)	Narita Int'l (NRT / RJAA)	1592	1383
13	CJT583	B763	Hamilton/John C. Munro Int'l (CYHM)	Calgary Int'l (CYYC)	1725	1499
14	ATN3844	B763	Ontario Intl (KONT)	Dallas-Fort Worth Intl (KDFW)	1227	1066
15	TMN1	B763	Auckland (AKL / NZAA)	Sydney (SYD / YSSY)	1343	1167
16	JA616A	B763	Palau Int'l (Babelthuap/Koror) (ROR / PTRO)	Narita Int'l (NRT / RJAA)	2035	1768
17	FDX1026	B763	Newark Liberty Intl (KEWR)	Los Angeles Intl (KLAX)	2517	2187
18	TAM3751	B763	Eduardo Gomes Int'l (MAO / SBEG)	São Paulo-Guarulhos Int'l (GRU / SBGR)	1678	1458
19	GTI3602	B763	March Arb (KRIV)	Houston Bush Int'ctl (KIAH)	1403	1219
20	UAL855	B763	Jorge Chavez Int'l (LIM / SPJC)	Houston Bush Int'ctl (KIAH)	3195	2776
Routes with more than 3000 nm range						
1	UAL957	B763	Geneva Cointrin Int'l (GVA / LSGG)	Newark Liberty Intl (KEWR)	3987	3465
2	TAM8111	B763	Leonardo da Vinci Int'l (Fiumicino Int'l) (FCO / LIRF)	São Paulo-Guarulhos Int'l (GRU / SBGR)	5868	5099
3	UAL883	B763	London Heathrow (LHR / EGLL)	Newark Liberty Intl (KEWR)	3561	3094
4	TAM8179	B763	Lisbon / Lisboa,Portela (Lisbon) (LIS / LPPT)	São Paulo-Guarulhos Int'l (GRU / SBGR)	4936	4289
5	LPE2476	B763	Jorge Chavez Int'l (LIM / SPJC)	Los Angeles Intl (KLAX)	4229	3675
6	CFG2282	B763	Zanzibar (ZNZ / HTZA)	Frankfurt Int'l (FRA / EDDF)	4304	3740
7	CFG3839	B763	Seychelles Int'l (SEZ / FSIA)	Frankfurt Int'l (FRA / EDDF)	4704	4088

The following routes were considered for the B757 aircraft:

Boeing 757						
					Range	
Nº	Ident	Type	Origin	Destination	miles	nm
Routes with less than 1000 nm range						
1	FDX1076	B757	Piedmont Triad Intl (KGSO)	Minneapolis/St Paul Intl (KMSP)	980	852
2	UPS353	B757	La Aurora Int'l (GUA / MGGT)	Miami Intl (KMIA)	1047	910
3	TUA554	B757	Sri Guru Ram Dass Jee International Airport (ATQ / VIAR)	Ashgabat (Ashkhabad) (ASB / UTAA)	1028	893
4	ICE440	B757	Keflavik Int'l (KEF / BIKF)	Manchester (MAN / EGCC)	1029	894
5	ATN1817	B757	Seattle-Tacoma Intl (KSEA)	Los Angeles Intl (KLAX)	956	831
6	ICE318	B757	Keflavik Int'l (KEF / BIKF)	Oslo, Gardermoen (OSL / ENGM)	1108	963
7	UPS554	B757	Louisville Intl (KSDF)	Minneapolis/St Paul Intl (KMSP)	623	541
8	ICE416	B757	Keflavik Int'l (KEF / BIKF)	Dublin Int'l (DUB / EIDW)	932	810
9	UPS1218	B757	Louisville Intl (KSDF)	Richmond Intl (KRIC)	491	427
10	UPS9785	B757	Louisville Intl (KSDF)	Dallas-Fort Worth Intl (KDFW)	733	637
11	UPS1134	B757	Philadelphia Intl (KPHL)	Albany Intl (KALB)	249	216
12	FDX1061	B757	Piedmont Triad Intl (KGSO)	Chicago O'Hare Intl (KORD)	670	582
13	FDX1065	B757	Piedmont Triad Intl (KGSO)	Hartsfield-Jackson Intl (KATL)	365	317
14	UPS1198	B757	Philadelphia Intl (KPHL)	Columbia Metropolitan (KCAE)	537	467
15	FDX1950	B757	Newark Liberty Intl (KEWR)	Chicago O'Hare Intl (KORD)	755	656
16	FDX1976	B757	Newark Liberty Intl (KEWR)	Pittsburgh Intl (KPIT)	348	302

Boeing 757						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
17	FDX1073	B757	Piedmont Triad Intl (KGSO)	Newark Liberty Intl (KEWR)	481	418
18	UPS1350	B757	Dallas-Fort Worth Intl (KDFW)	Tampa Intl (KTPA)	999	868
19	FDX1078	B757	Piedmont Triad Intl (KGSO)	Charleston Intl/AFB (KCHS)	223	194
20	FDX1988	B757	Newark Liberty Intl (KEWR)	Hartsfield-Jackson Intl (KATL)	801	696
21	UPS608	B757	Dallas-Fort Worth Intl (KDFW)	Chicago O'Hare Intl (KORD)	833	724
22	UPS1340	B757	Philadelphia Intl (KPHL)	Palm Beach Intl (KPBI)	1028	893
23	FDX1067	B757	Piedmont Triad Intl (KGSO)	Tampa Intl (KTPA)	638	554
24	FDX1982	B757	Newark Liberty Intl (KEWR)	Detroit Metro Wayne Co (KDTW)	525	456
25	FDX1074	B757	Piedmont Triad Intl (KGSO)	Orlando Intl (KMCO)	536	466
Routes with more than 1000 nm and less than 3000 nm range						
1	AAL1945	B757	Kahului (OGG / PHOG)	Phoenix Sky Harbor Intl (KPHX)	2887	2509
2	UPS952	B757	Louisville Intl (KSDF)	Metropolitan Oakland Intl (KOAK)	2020	1755
3	TOM4226	B757	London Gatwick (LGW / EGKK)	Tenerife South (Reina Sofia) (TFS / GCTS)	1811	1574
4	DAL2197	B757	Los Angeles Intl (KLAX)	John F Kennedy Intl (KJFK)	2714	2358
5	DAL1768	B757	Kahului (OGG / PHOG)	Seattle-Tacoma Intl (KSEA)	2741	2382
6	ICE204	B757	Keflavik Int'l (KEF / BIKF)	Copenhagen (CPH / EKCH)	1334	1159
7	DAL2222	B757	Kahului (OGG / PHOG)	Los Angeles Intl (KLAX)	2641	2295
8	ICE342	B757	Keflavik Int'l (KEF / BIKF)	Helsinki-Vantaa (HEL / EFHK)	1520	1321
9	UZB711	B757	Termez (TMJ / UTST)	Pulkovo (LED / ULLI)	2251	1956

Boeing 757						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
10	ICE306	B757	Keflavik Int'l (KEF / BIKF)	Stockholm-Arlanda (ARN / ESSA)	1333	1158
11	DAL1388	B757	Los Angeles Intl (KLAX)	Juan Santamaria Int'l (SJO / MROC)	2798	2431
12	DAL1394	B757	Los Angeles Intl (KLAX)	La Aurora Int'l (GUA / MGGT)	2239	1946
13	DAL1674	B757	Seattle-Tacoma Intl (KSEA)	Minneapolis/St Paul Intl (KMSP)	1453	1263
14	EXS223	B757	Leeds Bradford Int'l (LBA / EGNM)	Tenerife South (Reina Sofia) (TFS / GCTS)	1939	1685
15	TOM258	B757	London Gatwick (LGW / EGKK)	Rabil (BVC / GVBA)	2727	2370
16	UAL534	B757	Daniel K Inouye Intl (PHNL)	Los Angeles Intl (KLAX)	2370	2059
17	DAL1212	B757	Daniel K Inouye Intl (PHNL)	Los Angeles Intl (KLAX)	2738	2379
18	DAL1517	B757	McCarran Intl (KLAS)	Hartsfield-Jackson Intl (KATL)	1824	1585
19	DAL2711	B757	McCarran Intl (KLAS)	Detroit Metro Wayne Co (KDTW)	1801	1565
20	DAL1354	B757	Los Angeles Intl (KLAX)	Hartsfield-Jackson Intl (KATL)	2044	1776

The following routes were considered for the B787-9 aircraft:

Boeing 787-9						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
2	CSN3504	B789	Shanghai Hongqiao Int'l (SHA / ZSSS)	Guangzhou Baiyun Int'l (CAN / ZGGG)	732	636
3	SVA1037	B789	King Khalid Int'l (RUH / OERK)	King Abdulaziz Int'l (JED / OEJN)	529	460

Boeing 787-9						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
4	CCA1410	B789	Chongqing Jiangbei Int'l (CKG / ZUCK)	Beijing Capital Int'l (PEK / ZBAA)	910	791
5	CES5848	B789	Chengdu Shuangliu Int'l (CTU / ZUUU)	Kunming Changshui Int'l (KMG / ZPPP)	384	334
6	EVA872	B789	Hong Kong Int'l (HKG / VHHH)	Taiwan Taoyuan Int'l (TPE / RCTP)	502	436
7	CHH7695	B789	Beijing Capital Int'l (PEK / ZBAA)	Fuzhou Changle Int'l (FOC / ZSFZ)	994	864
8	ETD334	B789	King Abdulaziz Int'l (JED / OEJN)	Abu Dhabi Int'l (AUH / OMAA)	1003	872
Routes with more than 1000 nm and less than 3000 nm range						
1	ETD514	B789	Queen Alia Int'l (AMM / OJAI)	Abu Dhabi Int'l (AUH / OMAA)	1243	1080
2	LAN750	B789	Comodoro Arturo Merino Benitez Int'l (SCL / SCEL)	São Paulo-Guarulhos Int'l (GRU / SBGR)	1626	1413
3	SVA482	B789	Sir Seewoosagur Ramgoolam Int'l (MRU / FIMP)	King Abdulaziz Int'l (JED / OEJN)	3170	2755
4	ETD654	B789	Cairo Int'l (CAI / HECA)	Abu Dhabi Int'l (AUH / OMAA)	1479	1285
5	SVA375	B789	King Khalid Int'l (RUH / OERK)	Mohammed V Int'l (CMN / GMMN)	3294	2862
6	OMA675	B789	Seeb Int'l (MCT / OOMS)	King Abdulaziz Int'l (JED / OEJN)	1228	1067
7	CCA776	B789	Singapore Changi (SIN / WSSS)	Beijing Capital Int'l (PEK / ZBAA)	2793	2427
8	CSN3111	B789	Guangzhou Baiyun Int'l (CAN / ZGGG)	Beijing Capital Int'l (PEK / ZBAA)	1170	1017
Routes with more than 3000 nm range						

Boeing 787-9						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
1	KLM677	B789	Amsterdam Schiphol (AMS / EHAM)	Calgary Int'l (CYYC)	4459	3875
2	ETD485	B789	Brisbane (BNE / YBBN)	Abu Dhabi Int'l (AUH / OMAA)	3610	3137
3	ACA857	B789	London Heathrow (LHR / EGLL)	Toronto Pearson Int'l (CYYZ)	3550	3085
4	QFA10	B789	London Heathrow (LHR / EGLL)	Perth Int'l (PER / YPPH)	9026	7843
5	ACA8	B789	Hong Kong Int'l (HKG / VHHH)	Vancouver Int'l (CYVR)	6426	5584
6	CES737	B789	Shanghai Pudong Int'l (PVG / ZSPD)	Melbourne Tullamarine (MEL / YMML)	4987	4334
7	THA491	B789	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	Auckland (AKL / NZAA)	5944	5165
8	ETD461	B789	Melbourne Tullamarine (MEL / YMML)	Abu Dhabi Int'l (AUH / OMAA)	4425	3845
9	ACA62	B789	Incheon Int'l (ICN / RKSI)	Toronto Pearson Int'l (CYYZ)	6604	5739
10	ANZ283	B789	Singapore Changi (SIN / WSSS)	Auckland (AKL / NZAA)	5231	4546
11	CHH408	B789	Ben Gurion Int'l (TLV / LLBG)	Shanghai Pudong Int'l (PVG / ZSPD)	4963	4313
12	KAL123	B789	Incheon Int'l (ICN / RKSI)	Brisbane (BNE / YBBN)	4903	4261
13	ANZ87	B789	Auckland (AKL / NZAA)	Hong Kong Int'l (HKG / VHHH)	5704	4957
14	ANZ176	B789	Perth Int'l (PER / YPPH)	Auckland (AKL / NZAA)	3320	2885
15	VIR105	B789	London Heathrow (LHR / EGLL)	Seattle-Tacoma Intl (KSEA)	4791	4163
16	OMA105	B789	Seeb Int'l (MCT / OOMS)	Manchester (MAN / EGCC)	3725	3237
17	ACA881	B789	Charles de Gaulle/Roissy (CDG / LFPG)	Toronto Pearson Int'l (CYYZ)	3900	3389

Boeing 787-9						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
18	CXA806	B789	Vancouver Int'l (CYVR)	Xiamen Gaoqi Int'l (XMN / ZSAM)	6371	5536
19	ACA18	B789	Taiwan Taoyuan Int'l (TPE / RCTP)	Vancouver Int'l (CYVR)	6008	5221
20	ANZ78	B789	Taiwan Taoyuan Int'l (TPE / RCTP)	Auckland (AKL / NZAA)	5733	4982
21	ANA880	B789	Sydney (SYD / YSSY)	Tokyo Int'l (Haneda) (HND / RJTT)	4863	4226
22	OMA101	B789	Seeb Int'l (MCT / OOMS)	London Heathrow (LHR / EGLL)	3630	3154
23	AAL128	B789	Shanghai Pudong Int'l (PVG / ZSPD)	Dallas-Fort Worth Intl (KDFW)	7690	6682
24	AAL26	B789	Tokyo Int'l (Haneda) (HND / RJTT)	Los Angeles Intl (KLAX)	5511	4789

The following routes were considered for the B787-8 aircraft:

Boeing 787-8						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
Routes with less than 1000 nm range						
1	CSN3367	B788	Guangzhou Baiyun Int'l (CAN / ZGGG)	Wuhan Tianhe (WUH / ZHHH)	514	447
2	QTR1079	B788	Kuwait Int'l (KWI / OKBK)	Hamad Int'l (DOH / OTHH)	353	307
3	REU276	B788	Roland Garros (RUN / FMEE)	Dzaoudzi Pamandzi Int'l (DZA / FMCZ)	878	763
4	CXA846	B788	Shenzhen Bao'an Int'l (SZX / ZGSZ)	Xiamen Gaoqi Int'l (XMN / ZSAM)	304	264

Boeing 787-8						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
5	QTR1072	B788	Hamad Int'l (DOH / OTHH)	Kuwait Int'l (KWI / OKBK)	353	307
6	JAL879	B788	Narita Int'l (NRT / RJAA)	Shanghai Pudong Int'l (PVG / ZSPD)	1117	971
Routes with more than 1000 nm and less than 3000 nm range						
1	ETH846	B788	Cape Town Int'l (CPT / FACT)	Bole Int'l (ADD / HAAB)	3253	2827
2	QTR151	B788	Hamad Int'l (DOH / OTHH)	Barajas Int'l (MAD / LEMD)	3315	2881
3	LAN536	B788	Comodoro Arturo Merino Benitez Int'l (SCL / SCEL)	Jorge Chavez Int'l (LIM / SPJC)	1532	1331
4	QTR23	B788	Hamad Int'l (DOH / OTHH)	Manchester (MAN / EGCC)	3365	2924
5	THA436	B788	Jakarta-Soekarno-Hatta Int'l (CGK / WIII)	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	1429	1242
6	CSN6831	B788	Sanya Phoenix Int'l (SYX / ZJSY)	Urumqi Diwopu Int'l (URC / ZWWW)	2182	1896
7	AIC315	B788	Hong Kong Int'l (HKG / VHHH)	Indira Gandhi Int'l (DEL / VIDP)	2330	2025
8	KQA762	B788	Jomo Kenyatta Int'l (NBO / HKJK)	OR Tambo Int'l (JNB / FAOR)	1811	1574
9	TGW703	B788	Kansai Int'l (KIX / RJBB)	Singapore Changi (SIN / WSSS)	3050	2650
10	AIC139	B788	Indira Gandhi Int'l (DEL / VIDP)	Ben Gurion Int'l (TLV / LLBG)	2518	2188
11	ANA805	B788	Narita Int'l (NRT / RJAA)	Suvarnabhumi Bangkok Int'l (BKK / VTBS)	2892	2513
Routes with more than 3000 nm range						
1	ETH508	B788	Lome (LFW / DXXX)	Newark Liberty Intl (KEWR)	5184	4505

Boeing 787-8						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
2	RAM216	B788	Mohammed V Int'l (CMN / GMMN)	Hamad Int'l (DOH / OTHH)	3567	3100
3	CXA826	B788	Charles de Gaulle/Roissy (CDG / LFPG)	Fuzhou Changle Int'l (FOC / ZSFZ)	5983	5199
4	AMX15	B788	São Paulo-Guarulhos Int'l (GRU / SBGR)	Lic. Benito Juarez Int'l (MEX / MMMX)	4624	4018
5	UAL919	B788	London Heathrow (LHR / EGLL)	Washington Dulles Intl (KIAD)	3671	3190
6	BAW249	B788	London Heathrow (LHR / EGLL)	Rio de Janeiro/Galeao Intl (GIG / SBGL)	5576	4845
7	QTR851	B788	Penang Int'l (PEN / WMKP)	Hamad Int'l (DOH / OTHH)	3503	3044
8	JAL8792	B788	Kansai Int'l (KIX / RJBB)	Daniel K Inouye Intl (PHNL)	4193	3644
9	AVA17	B788	Barajas Int'l (MAD / LEMD)	Jose Maria Cordova Int'l (MDE / SKRG)	5236	4550
10	TFL337	B788	Amsterdam Schiphol (AMS / EHAM)	Juan Gualberto Gomez Int'l (VRA / MUVR)	4840	4206
11	UAL808	B788	Beijing Capital Int'l (PEK / ZBAA)	Washington Dulles Intl (KIAD)	7179	6238
12	TOM176	B788	Manchester (MAN / EGCC)	Cancun Int'l (CUN / MMUN)	4903	4261
13	TGW700	B788	Kansai Int'l (KIX / RJBB)	Daniel K Inouye Intl (PHNL)	4114	3575
14	LOT21	B788	Warsaw Frederic Chopin (WAW / EPWA)	Los Angeles Intl (KLAX)	6008	5221
15	OMA131	B788	Seeb Int'l (MCT / OOMS)	Charles de Gaulle/Roissy (CDG / LFPG)	3471	3016

Boeing 787-8						
№	Ident	Type	Origin	Destination	Range	
					miles	nm
16	CHH466	B788	Ben Gurion Int'l (TLV / LLBG)	Guangzhou Baiyun Int'l (CAN / ZGGG)	4738	4117
17	KQA113	B788	Charles de Gaulle/Roissy (CDG / LFPG)	Jomo Kenyatta Int'l (NBO / HKJK)	4040	3511
18	QTR931	B788	Clark International (CRK / RPLC)	Hamad Int'l (DOH / OTHH)	4485	3897
19	AAL49	B788	Charles de Gaulle/Roissy (CDG / LFPG)	Dallas-Fort Worth Intl (KDFW)	5164	4487
20	TGW13	B788	Sydney (SYD / YSSY)	Singapore Changi (SIN / WSSS)	3916	3403
21	ANA178	B788	Narita Int'l (NRT / RJAA)	Seattle-Tacoma Intl (KSEA)	4862	4225
22	AAL71	B788	Frankfurt Int'l (FRA / EDDF)	Dallas-Fort Worth Intl (KDFW)	5136	4463
23	JAL18	B788	Narita Int'l (NRT / RJAA)	Vancouver Int'l (CYVR)	4722	4103

Annex VI Detailed data about airlines fleet.

According to a study by Flight Global, which was conducted to search for a gap in the aircraft market, seating capacities and range capabilities of single-aisle and small twin-aisle types of aircraft were estimated and predicted. The results are shown in Figure 88. The debate about future aircraft to fill the Middle of the Market bearing various names like MMA (Middle of the Market Aircraft) or NMA (New Midsize Airplane) has gained more traction, having been a topic of discussion for several years now. Boeing's specialists said that their NMA development program shall enter into service in 2024 or 2025 and Boeing forecasts a total market of 4,000 to 5,000 MoM aircraft. Thus the Airbus A321neo and A330neo take a portion of this, leaving a demand for some 2,000 to 3,000 units.

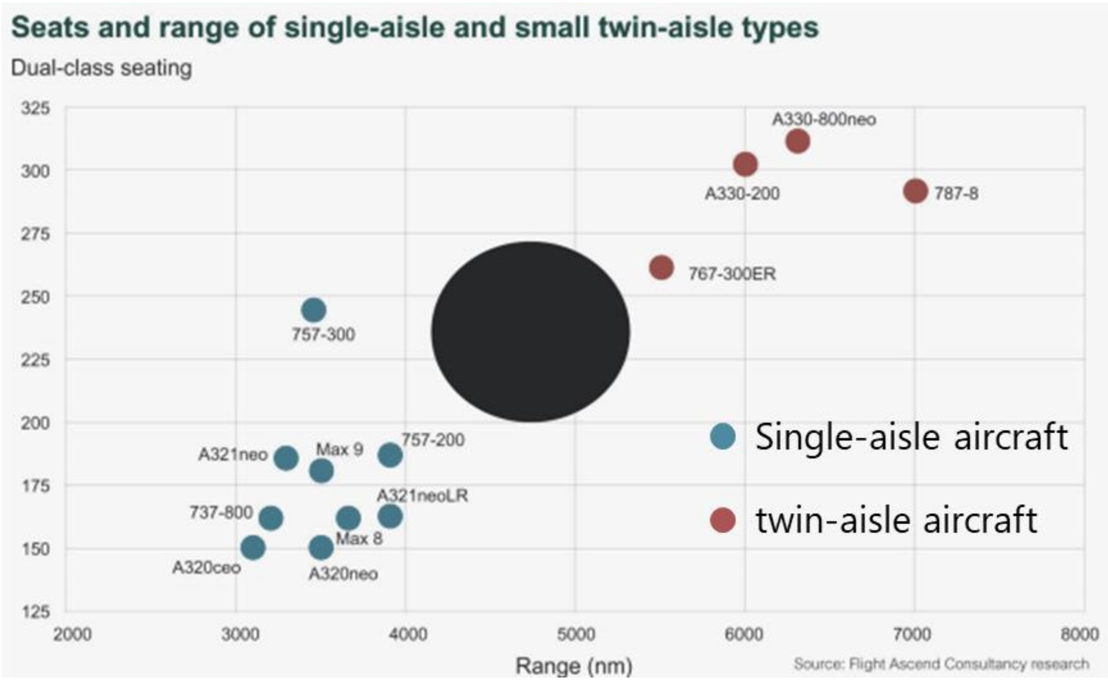


Figure 88. Seats and range of single-aisle and small twin-aisle types of aircraft

Capacity and range of the in-production single-aisles are certainly increasing. The A321neo is already able to carry up to 240 passengers in a high-density layout with the Airbus Cabin Flex and a new door configuration. In A321neoLR version, the range is increased to 4,000nm by using new technologies.

Boeing is responding with its Max 10X proposal, which is a further 66in (1.67m) stretch beyond the Max 9 and will enable a capacity of up to 230 seats. Such aircraft has 5% lower operating trip and seat-mile costs than an A321neo. Entry into service will be around 2020. But there is a danger of cannibalisation between Max 8, 9 and 10.

One of the key questions is how much range to build into an MoM design. Analysis from Flightglobal flight data for the year 2017 shows that the average twin-aisle has 304 seats and the average flight distance is around 2,570nm (Figure 89). By contrast, the average single-aisle has 164 seats and 718nm flight distance.

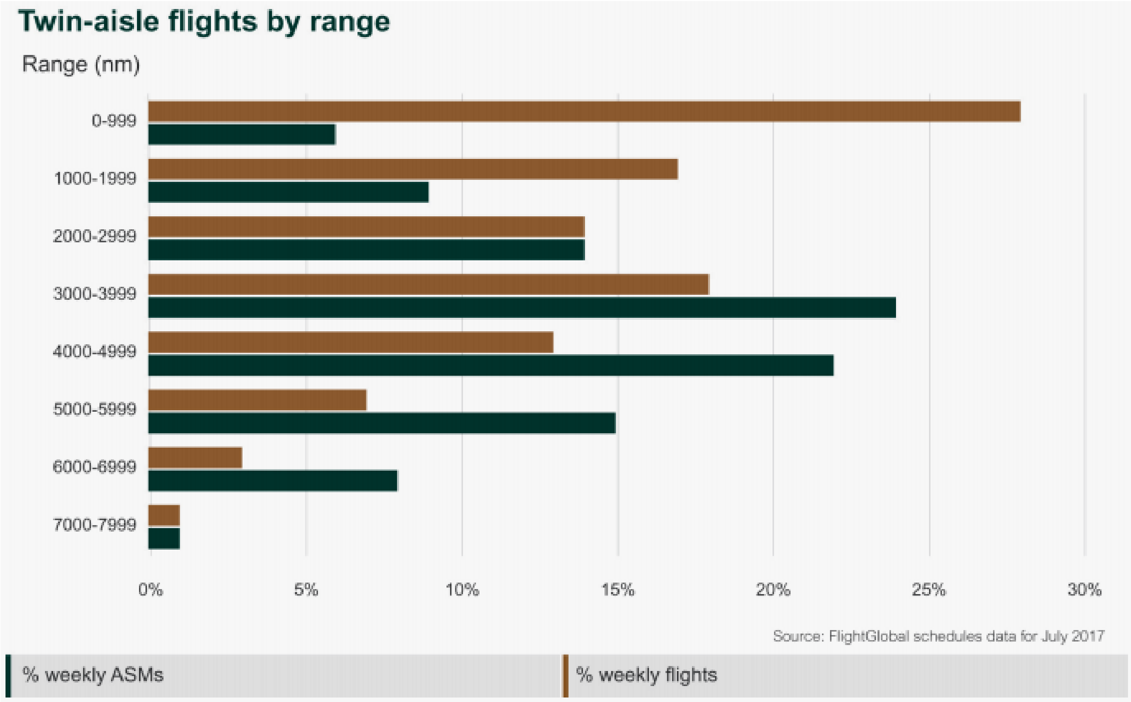


Figure 89. Twin-aisle flights by the range

As can be seen in Figure 89, the most twin-aisle flights being operated per week are actually on routes below 1,000nm – some 28%, although these only generate 6% of the available seat miles (ASMs). At the other end of the scale, the ultra-long range-flights of over 7,000nm represent just 1% of both flights and ASMs.

About 90% of twin-aisle flights, generating 75% of ASMs, are on routes under 5,000nm, which is the core of the MoM proposals. Some airlines are being creative in using their twin-aisles, for example flying an A330-200 from China to Europe one day and on shorter flights within China the next.

Analysing only twin-aisle aircraft with configurations of below 260 seats, these have an average of 234 seats and 2,670nm flight distance, with 60% of ASMs below 4,000nm and 82% below 5,000nm. If considering only the A330-200 and 767, the most popular small twin-aisles in operation, the figures are even higher at 66% and 92%, with the longest current route at 6,000nm.

So an MoM design with a range of 4,800nm to 5,200nm looks to be in the right area to cover the vast majority of current operations with current and previous generation small twins, as well as providing increased range above where single-aisles operate. The 757s currently have an average of 1,580nm flight distance, with the longest routes at 3,400nm. A key question is what engines will power the aircraft? The improvements in wing technology and aerodynamic efficiency are reducing the thrust requirements in newer generation aircraft, so these are expected to be in the 40,000-45,000lb-thrust area.

Available options are expected to include the Rolls-Royce Advance or Ultrafan, a geared fan from Pratt & Whitney and an engine from CFM, General Electric's joint venture with Safran.

Recent launches (A350, A330neo and 777X) have had no engine choice so the trend to a sole source supplier may continue.

Technology will be key to driving efficiency and lowering operating cost. Boeing has already heavily invested in composite capability for the 787 and 777-X wing and technologies developed on the 787 will be mature by the time of a 797X launch. This should all help to limit development costs, which are likely at least to be in the $10-15 billion range.

Pricing of the new aircraft will also be crucial to its market appeal. Based on Flight Global suggestion, it will lie somewhere between larger single aisle in the $50 million and the A330neo and 787-8 in the $100-120 millions. The 767-300ER in its heyday was in the $70 million.

A seven-year development programme would be consistent with the 777X timescales, leading to entry into service in 2025. Airbus has been quite vocal to date about the A321neo and A322neo being their solution. However, this cannot address all the capacity and range offered by a smaller twin-aisle [88].

Today, the main issue is the replacement of current in-service passenger aircraft B757, B767, A321 and A330-200. Table 4 presents a comparative analysis of the performance of the MoM aircraft [89].

Table 4. Comparative analysis of the MoM aircraft

Middle-of-the-market aircraft comparison

	737 Max 10	A321neo*	757-200	**NMA**	767-200ER	767-300ER	787-8	A330-200	A330-800
MTOW (t)	90**	97	115.6	**N/A**	156.5-179.2	172.4-186.9	227.9	230-242	242
Passengers	204	206	195	**200-270**	192	229	242	247	257
Range (nm)	3,300	4,000	4,000	**5,000****	4,600-6,400	4,500-5,600	7,850	7,250	7,500
Engine thrust (lb)	28k**	35k	40-43k	**50k****	52-62k	63k	70k	68-72k	68-72k
List price ($m)	129.9	129.5	N/A	**N/A**	N/A	209.8	239	238.5	259.9
Total orders	403	1,920	914	**N/A**	249	687	418	659	0

Note: *Spec data for A321LR variant **Data estimated. Note: Order total for 757-200 excludes PF, for 767-200ER/300ER includes all -200/300 pax versions
Source: Manufacturers/FlightGlobal and Flight Fleets Analyzer

Many airlines have expressed interest in the NMA, either as replacements for existing types or as a vehicle to grow their fleets or launch new mid-range routes. Generally, new programmes are launched on replacement demand, as this is easier to evaluate than growth opportunities lying several years ahead. It is therefore instructive to consider which airlines have mid-market aircraft in their fleets today and the age profile of these types.

Assuming an EIS of 2026, operators would be looking to replace aircraft that would be more than 15 years old at that point in time. The chart shows the age profile of the mid-market fleet in 2026, based on the current in-service passenger fleets of Boeing 757s, 767s, Airbus A321s and A330-200s (Figure 90). The small fleets remaining of A300s and A310s will have been replaced well before 2026 and are excluded. The oldest 787-8s were built in 2011 and are unlikely to be replaced with initial NMA orders.

This shows that half of the current fleet will be less than 15 years of age by 2026. Aircraft that will be more than 30 years of age will almost certainly have been retired by that point. That leaves around 900 aircraft aged 15-25 years of age. These include 420 A321s, 270 A330-200s, 90 757s and 130 767s. Thus, the NMA cannot really be said to be a 757/767 replacement, as is too late. From Boeing's perspective, it may well be attractive to capture current Airbus A321neo.

The largest current operators of these mid-market types are the three US majors American, Delta and United, followed by the three largest Chinese airlines (China Southern, China Eastern, Air China). These six airlines fly over 1,000 aircraft in the size bracket, almost one-third of the total fleet. They also represent about a third of the aircraft in the 15-25-year age bracket. However, American has committed to order more 787-8s to replace its remaining 767 fleet, and will likely have replaced all 757s by the mid-2020s. Delta thus appears to be a key potential customer, as does United. Neither has ordered a direct replacement for its 767 fleet yet, and Delta still needs to place more orders to supplant its younger 757s. The three Chinese majors will also be significant potential operators, primarily for growth, but Airbus has a strong A321/A330-200 presence with them.

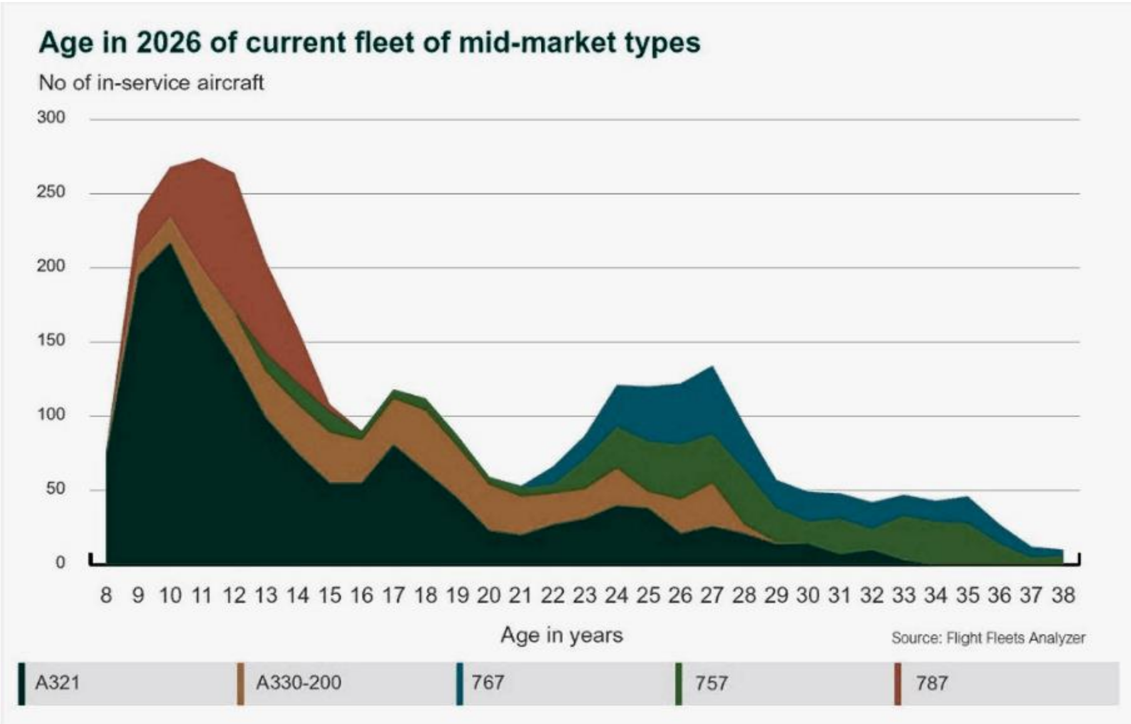


Figure 90. Age in 2026 of the current fleet of mid-market types

Beyond these six airlines, there are relatively few operators with large replacement needs. Only Turkish Airlines, Vietnam Airlines, Air Canada, Japan Airlines, Air France and Air India have more than 20 aircraft in the 15-25 age bracket by 2026 (Figure 91), but several already have aircraft orders aimed at replacing some of them. Operating lease companies are also likely to be enthusiastic early adopters, based on their penetration of the 767-300ER, 787, A330-200 and A321 fleets.

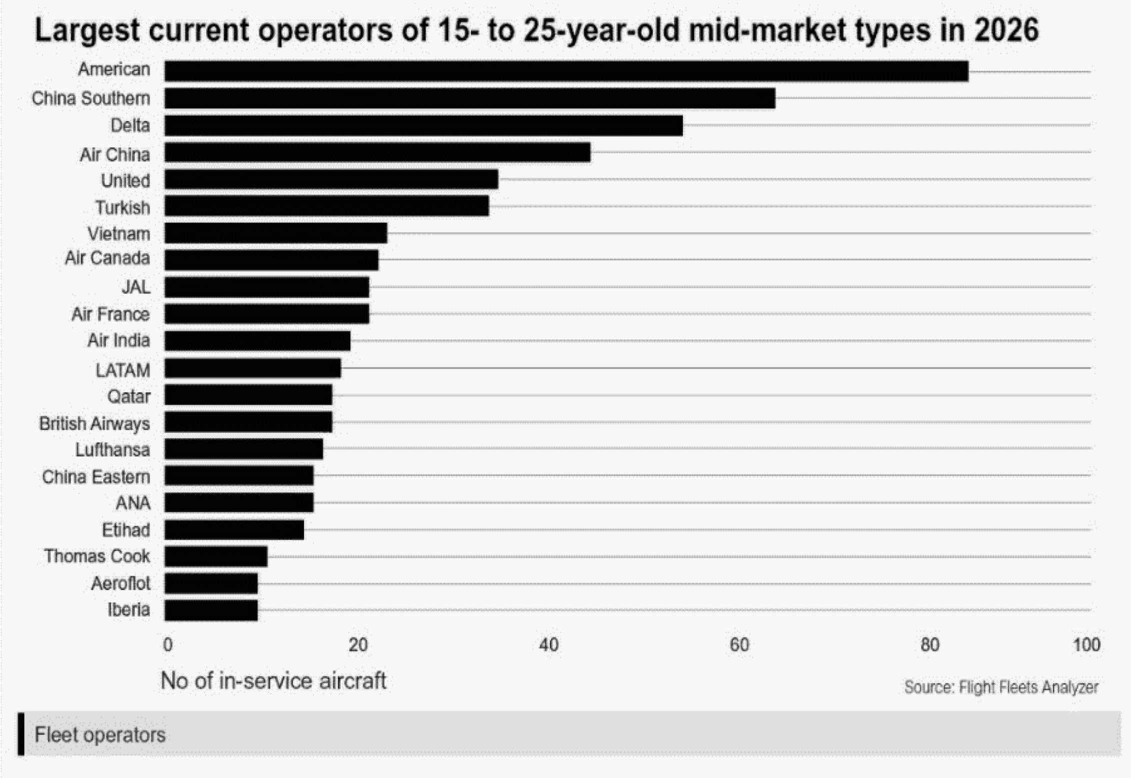


Figure 91. Largest current operators of 15- to 25-year-old mid-market types in 2026

Thus, the launch timing of the NMA thus appears to depend on the availability of a suitable engine or engines. The EIS date would be expected to be at least eight years, from this point. There is unlikely to be a shortage of prospective launch customers, but many will have already replaced their current mid-market fleets by 2025 or 2026. Thus, the prospects for the aircraft seem to depend more on offering something new to the market, in terms of operating costs and payload-range capability, to satisfy industry growth [90].

We will analyse the airlines that operate mid-market aircraft, as well as the main operators of B757 and B767.

AVI.1 European airlines

In Europe, major airlines are practically united in three groups: Lufthansa, Air France-KLM Group and IAG (British Airways). But, besides them, there are other significant players in the airline industry, such as Iberia, Austrian Airlines, Turkish Airlines, etc.

In Europe, all airlines are actively replacing aircraft. Due to rising fuel prices, demand for slightly larger 170-229 seat aircraft is increasing, such as the A321 and B737MAX-10. The number of seats on the A320 and B737-800 has also increased from 150 to 180 with higher density, and recently there is no much difference between large airlines and LCC [91].

AVI.1.1 Lufthansa airline

Lufthansa is the national airline of Germany, the largest European concern and one of the largest airlines in the world. Table 5, Figure 92 and Figure 92 display information about Lufthansa fleet, the number and the average age of the aircraft.

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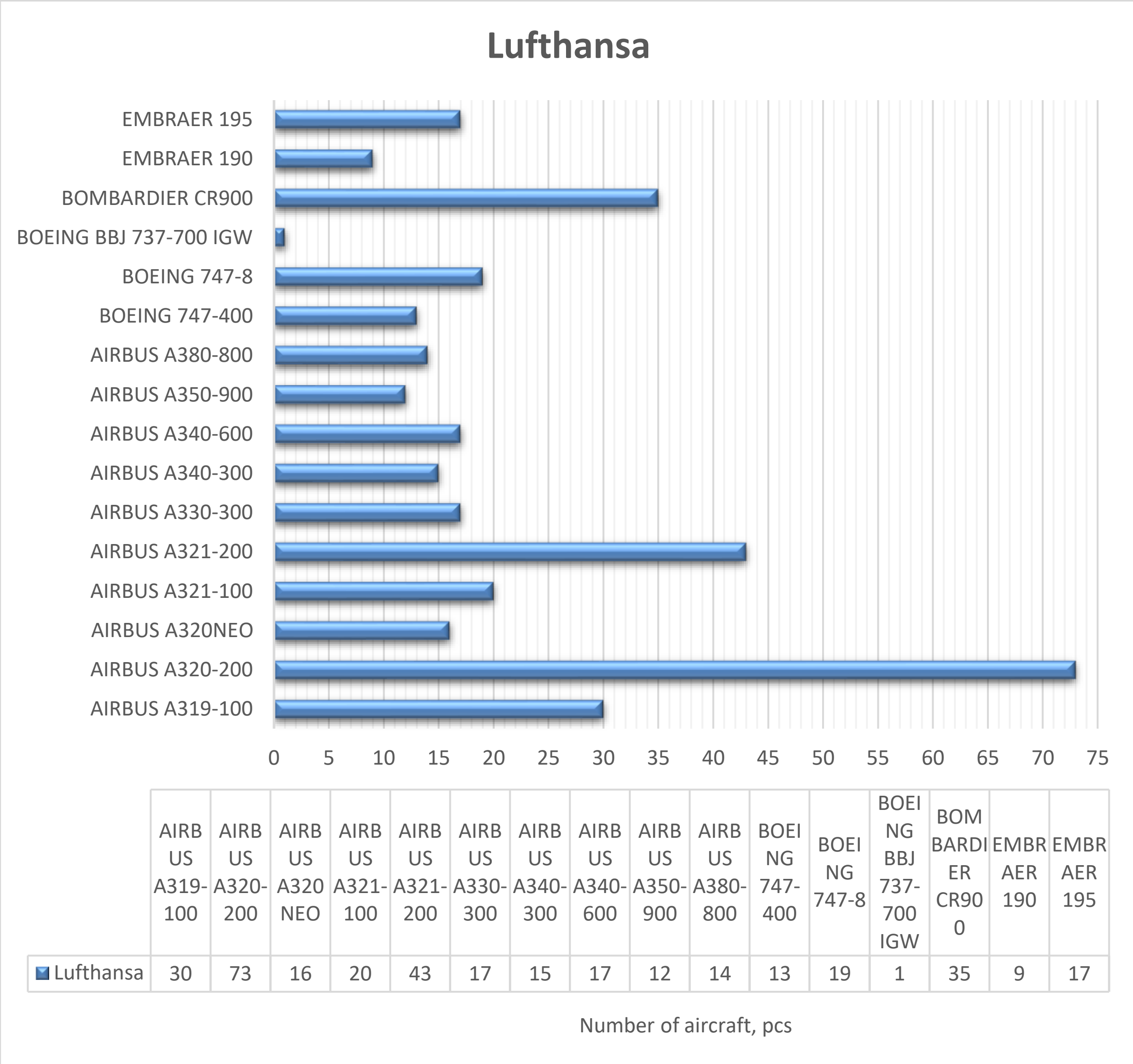
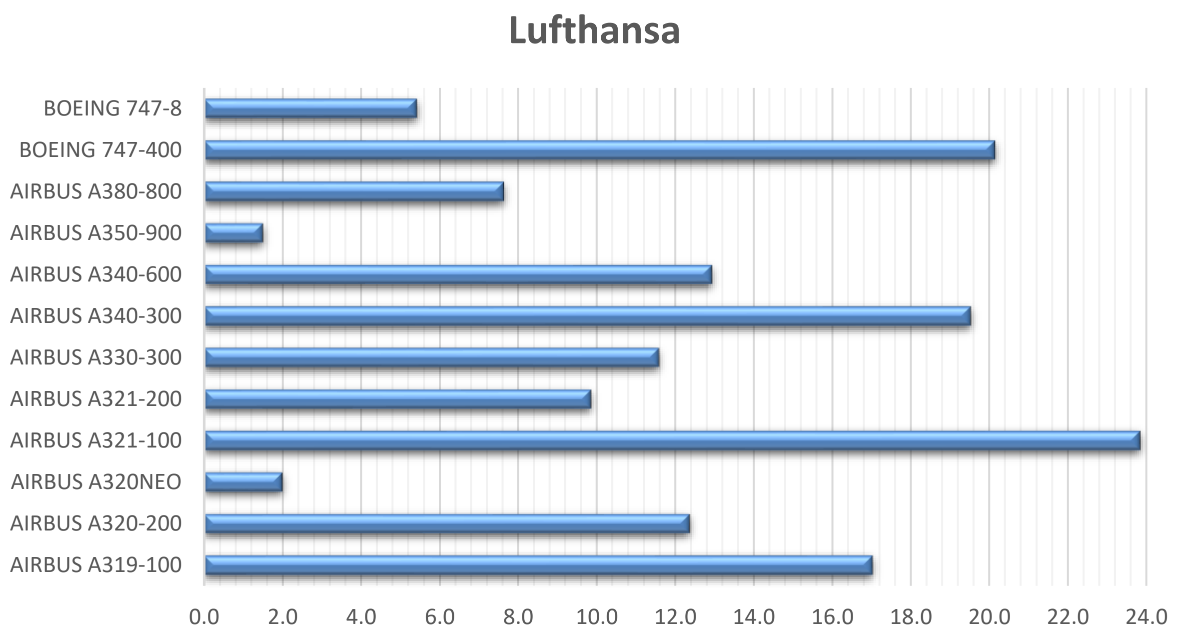


Table 5. Airline fleet, number and age of the aircraft

No.	Aircraft type	Aircraft age,			

		years		Number of aircraft, pcs	Average age of aircraft, years	New orders, pcs
		Min	Max			
1	Airbus A319-100	6	23	30	17.0	-
2	Airbus A320-200	1	30	73	12.4	7
3	Airbus A320neo	1	3	16	2.0	99
4	Airbus A321-100	21	26	20	23.9	-
5	Airbus A321-200	4	20	43	9.9	-
6	Airbus A330-300	5	15	17	11.6	-
7	Airbus A340-300	17	23	15	19.5	-
8	Airbus A340-600	10	16	17	12.9	-
9	Airbus A350-900	1	2	12	1.5	13
10	Airbus A380-800	4	10	14	7.6	-
11	Boeing 747-400	17	23	13	20.2	-
12	Boeing 747-8	4	7	19	5.4	-
13	EMBRAER 195	-	-	17	-	-
14	EMBRAER 190	-	-	9	-	-
15	BOMBARDIER CR900	-	-	35	-	-
16	BOEING BBJ 737-700	-	-	1	-	-
17	Airbus A321neo	-	-	-	-	41
18	Boeing 777-9X	-	-	-	-	20



	AIRBUS A319-100	AIRBUS A320-200	AIRBUS A320NEO	AIRBUS A321-100	AIRBUS A321-200	AIRBUS A330-300	AIRBUS A340-300	AIRBUS A340-600	AIRBUS A350-900	AIRBUS A380-800	BOEING 747-400	BOEING 747-8
Lufthansa	17.0	12.4	2.0	23.9	9.9	11.6	19.5	12.9	1.5	7.6	20.2	5.4

Average age of aircraft, years

Figure 92. The average age of aircraft type in the airline fleet

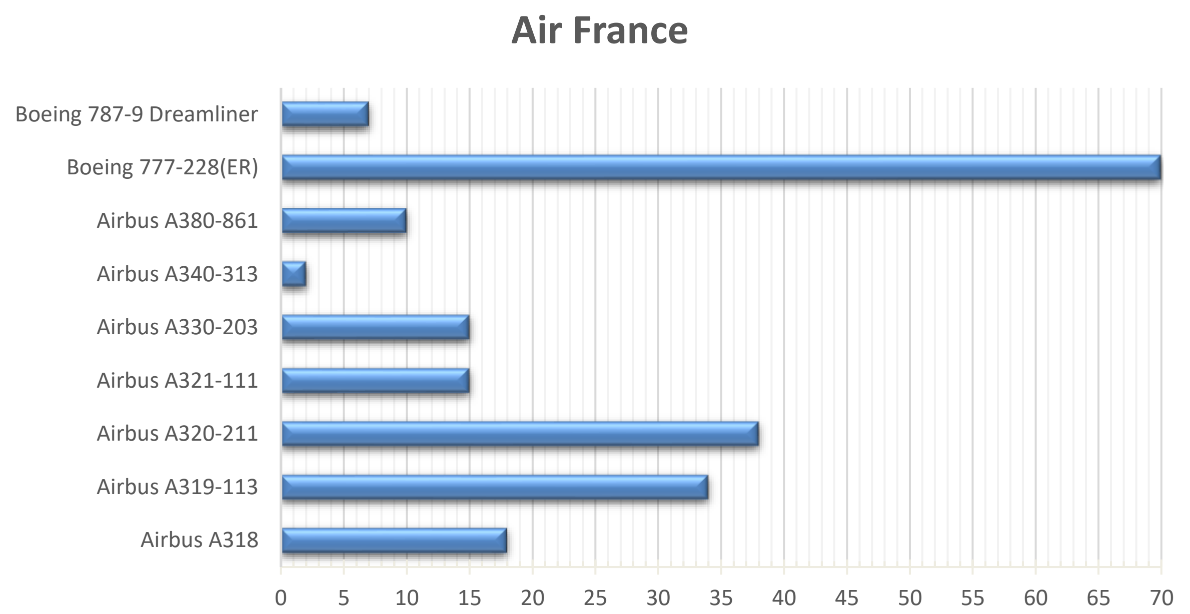
The average age of the airline fleet is about 12 years. In general, the airline fleet is quite young and constantly updated. So, the company plans to replace the Boeing 747-400 fleet in the period from 2020 to 2025 with Boeing 777-9X aircraft. The company has ordered 13 Airbus A350-900 aircraft that will be delivered by2023. There are also firm orders for the Airbus A320-200, A320neo aircraft [92]–[96].

AVI.1.2 Air France airlines

Air France is a subsidiary of the Air France-KLM Group. Table 6, Figure 93 and Figure 94 display information about the Air France fleet, the number and the average age of the aircraft.

Table 6. Airline fleet, number and age of the aircraft

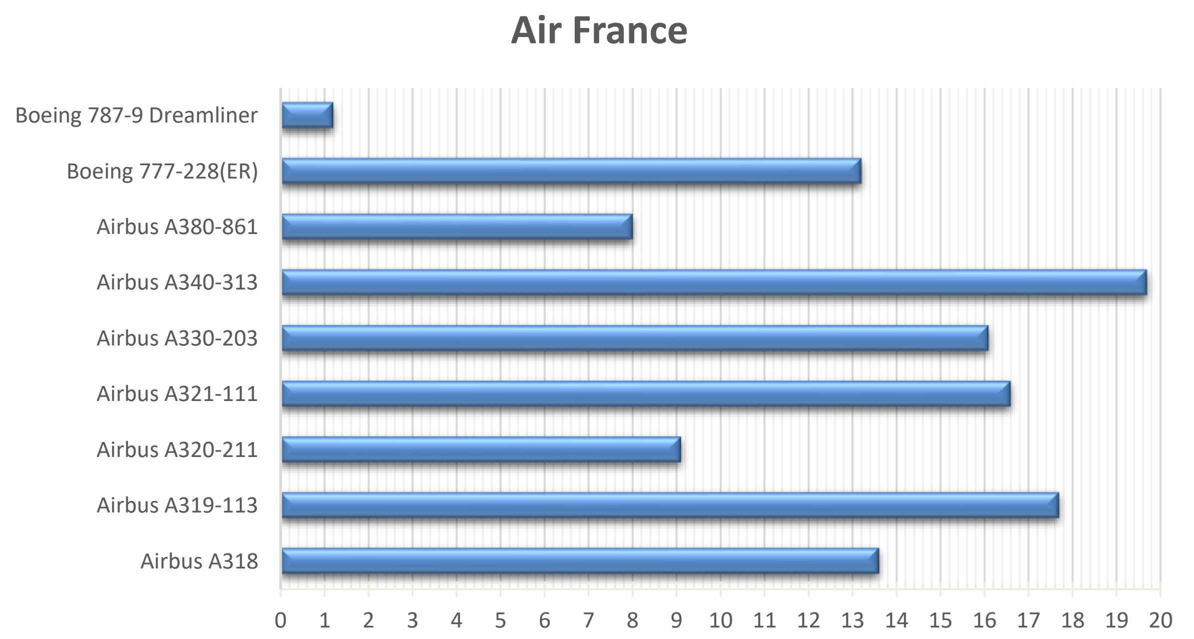
No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft, years	New orders, pcs
1	Airbus A318	18	13,6	-
2	Airbus A319-113	34	17,7	-
3	Airbus A320-211	38	9,1	-
4	Airbus A321-111	15	16,6	-
5	Airbus A330-203	15	16,1	-
6	Airbus A340-313	2	19,7	-
7	Airbus A380-861	10	8	-
8	Boeing 777-228(ER)	70	13,2	-
9	Boeing 787-9 Dreamliner	7	1,2	11
10	Airbus A350-900	-	-	21



	Airbus A318	Airbus A319-113	Airbus A320-211	Airbus A321-111	Airbus A330-203	Airbus A340-313	Airbus A380-861	Boeing 777-228(ER)	Boeing 787-9 Dreamliner
Air France	18	34	38	15	15	2	10	70	7

Number of aircraft, pcs

Figure 93. Number of aircraft in the airline fleet



	Airbus A318	Airbus A319-113	Airbus A320-211	Airbus A321-111	Airbus A330-203	Airbus A340-313	Airbus A380-861	Boeing 777-228(ER)	Boeing 787-9 Dreamliner
Air France	13.6	17.7	9.1	16.6	16.1	19.7	8	13.2	1.2

Figure 94. The average age of aircraft type in the airline fleet

According to the analysis, the average age of the airline fleet is about 10 years. In general, the airline fleet is quite young and constantly updated. Airbus aircraft dominate the airline fleet. In the near future, there is no need to replace the air fleet [97]–[100].

AVI.1.3 KLM airline

Royal Dutch Airlines (KLM) operates an extensive network of routes, connecting 360 cities in almost 80 countries of the world. KLM has several subsidiaries, including Transavia CV, Martinair Holland NV, KLM Cityhopper BV and others, as well as shares of the airline in Kenya. At the beginning of 2016, the KLM fleet consisted of 115 aircraft, among which Airbus and Boeing occupy a significant place (Table 7). Since 2004, KLM has been part of Air France-KLM.

Table 7. KLM airline fleet and its average age

No.	Aircraft	Number of aircraft in 2018	Aircraft age, years		Average age of aircraft type	Ordered
			Min	Max		
1	Airbus A330-200	8	8,4	13,5	11	0
2	Airbus A330-300	5	4,3	7	5,5	0
3	Airbus A350-900	0	-	-	-	7
4	Boeing 737-700	18	7,3	10,5	9	0
5	Boeing 737-800	27	4,9	20	12,5	4
6	Boeing 737-900	5	14,8	17,7	16,5	0
7	Boeing 747-400	15	25,9	28,9	27,5	0
8	Boeing 777-200ER	15	11,8	15,4	13	0
9	Boeing 777-300ER	14	1,4	11	5,6	0
10	Boeing 787-9	12	0,5	3,3	2,5	1
11	Boeing 787-10	0	-	-	-	8

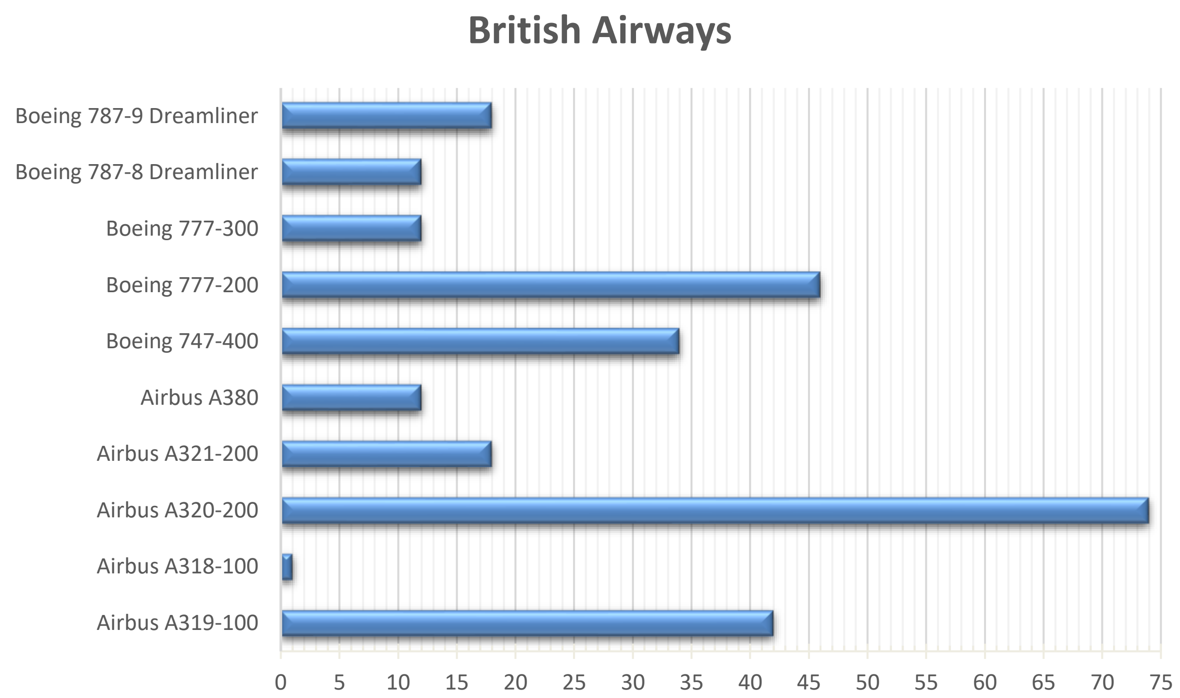
KLM and its partner airlines operate a network of routes connecting more than 360 cities in 78 countries on five continents. KLM transports people and goods both within the Netherlands and to other countries of the world.

AVI.1.4 British Airways airline

British Airways is the largest airline and national air carrier of Great Britain, one of the largest in Europe. It has the largest fleet in Great Britain. Table 8, Figure 95 and Figure 96 display information about the British Airways fleet, the number and the average age of the aircraft.

Table 8. Airline fleet, number and age of the aircraft

No.	Aircraft type	Aircraft age, years		Average age of aircraft, years	Number of aircraft, pcs	New orders, pcs
		Min	Max			
1	Airbus A319-100	7	20	15.9	42	-
2	Airbus A318-100	-	10	10	1	-
3	Airbus A320-200	1	17	9.0	74	18
4	Airbus A321-200	7	15	11.2	18	-
5	Airbus A380	3	6	4.8	12	-
6	Boeing 747-400	20	29	22.3	34	-
7	Boeing 777-200	10	24	19.4	46	-
8	Boeing 777-300	5	9	6.8	12	4
9	Boeing 787-8	1	6	4.1	12	-
10	Boeing 787-9	1	4	3.1	18	-
11	Airbus A350-1000	-	-	-	-	18



	Airbus A319-100	Airbus A318-100	Airbus A320-200	Airbus A321-200	Airbus A380	Boeing 747-400	Boeing 777-200	Boeing 777-300	Boeing 787-8 Dreamliner	Boeing 787-9 Dreamliner
British Airways	42	1	74	18	12	34	46	12	12	18

Number of aircraft, pcs

Figure 95. Number of aircraft in the airline fleet

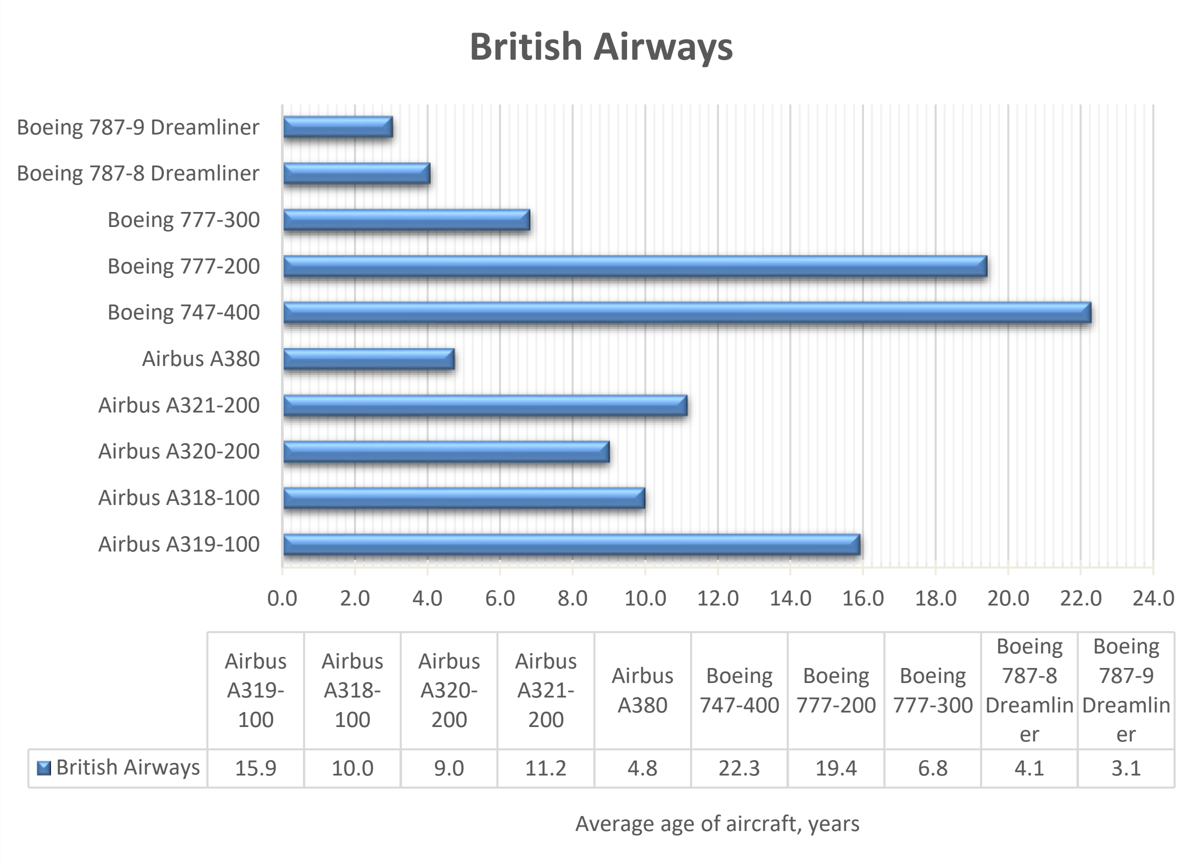


Figure 96. The average age of aircraft type in the airline fleet

According to the analysis, the average age of the airline fleet is about 12 years. In the near future, the company will require updating the fleet of Boeing 747-400 [101]–[104].

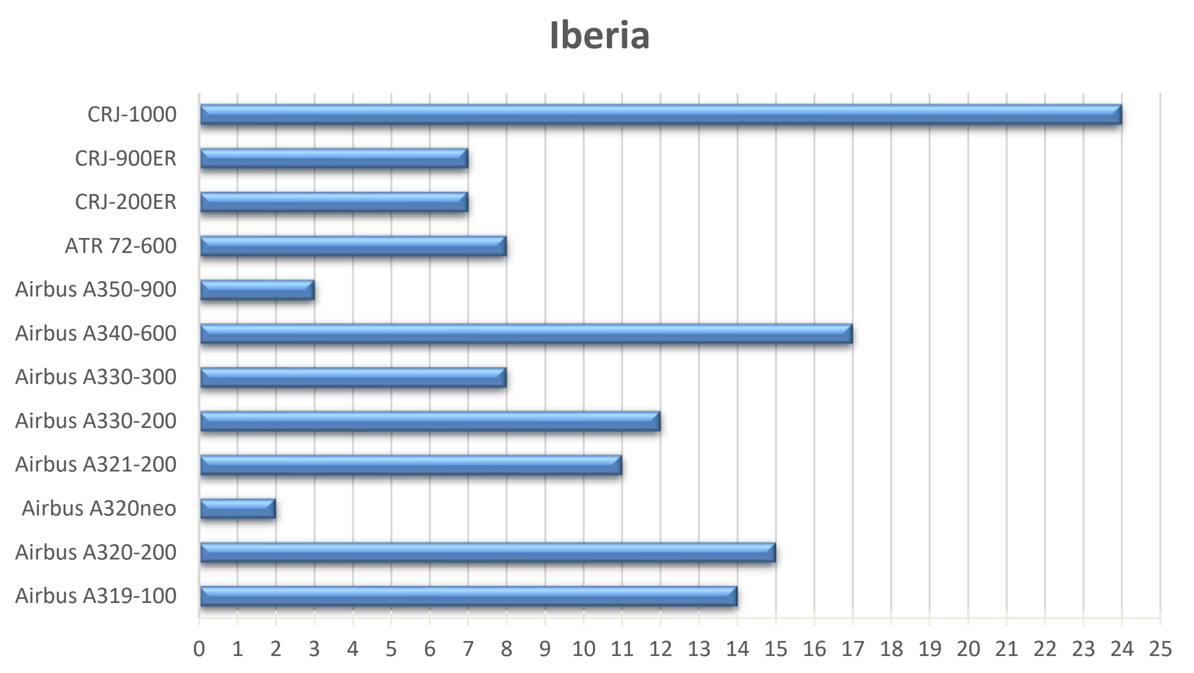
AVI.1.5 Iberia airline

Iberia is the national and largest airline in Spain. The Iberia Group operates flights to more than 115 destinations in 39 countries of the world on its own and to 90 destinations under code-sharing agreements with other airlines. Table 9, Figure 97 and Figure 98 display information about the Iberia fleet, the number and the average age of the aircraft.

Table 9. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	14	13,3	-
2	Airbus A320-200	15	12,1	-
3	Airbus A320neo	2	0,7	14

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
4	Airbus A321-200	11	15,8	-
5	Airbus A330-200	12	2,3	-
6	Airbus A330-300	8	5,5	-
7	Airbus A340-600	17	12,9	-
8	Airbus A350-900	3	0,5	15
9	ATR 72-600	8	6	-
10	CRJ-200ER	7	19	-
11	CRJ-900ER	7	12	-
12	CRJ-1000	24	2,9	-
13	Airbus A321neo	-	-	4



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A330-200	Airbus A330-300	Airbus A340-600	Airbus A350-900	ATR 72-600	CRJ-200ER	CRJ-900ER	CRJ-1000
Iberia	14	15	2	11	12	8	17	3	8	7	7	24

Figure 97. Number of aircraft in the airline fleet

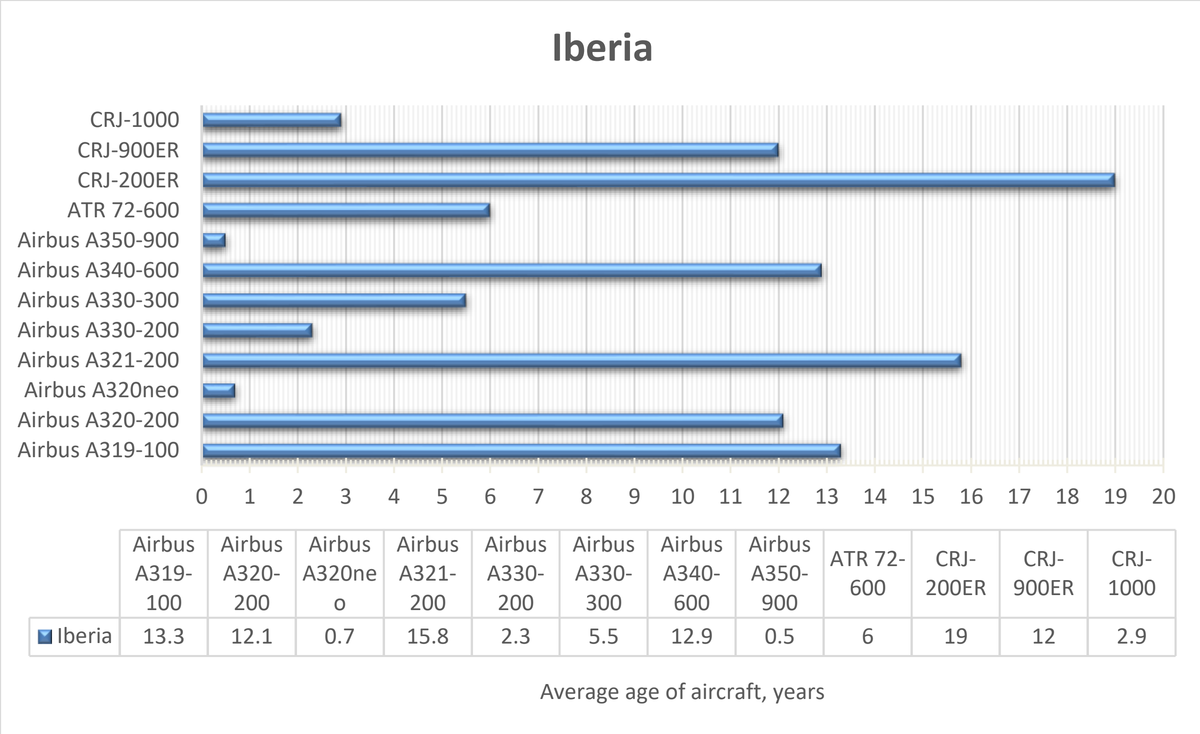


Figure 98. The average age of aircraft type in the airline

The average age of the Iberia fleet is about 9 years. The company has ordered 15 Airbus A350-900 aircraft to replace the A340-600 [105]–[107].

AVI.1.6 Austrian Airlines

Austrian Airlines is the largest Austrian carrier and operates a global route network of about 130 destinations, with 35 destinations in Central and Eastern Europe. Austrian Airlines currently operates a fleet of 83 aircraft (Table 10).

Table 10. Austrian Airlines fleet.

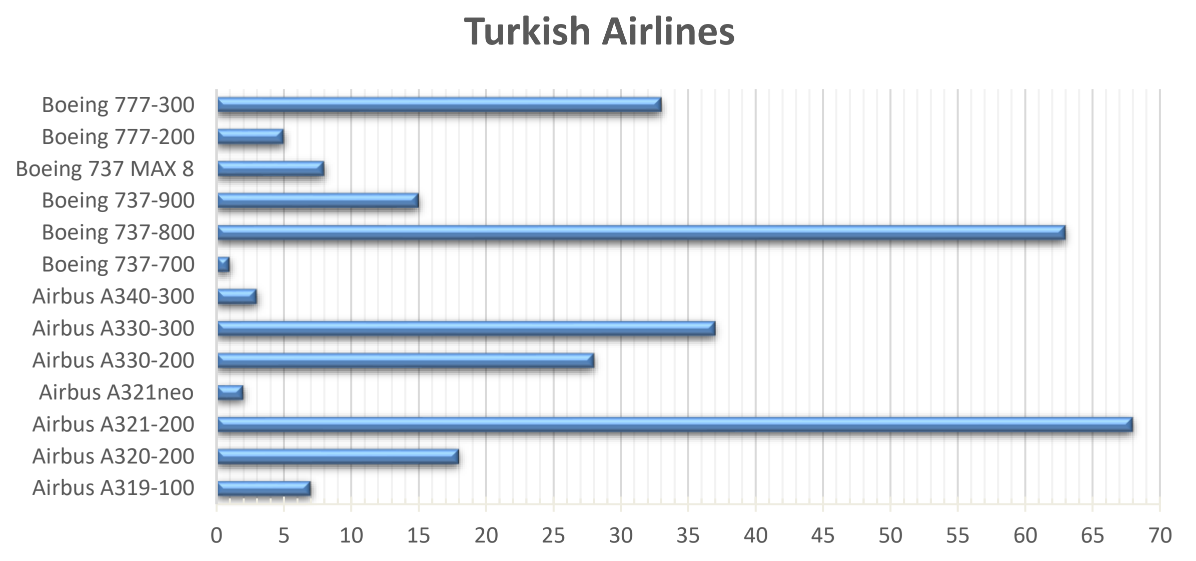
No.	Aircraft type	Number of aircraft, pcs	Aircraft age, years		Average age of aircraft type, years
			Min	Max	
1	Airbus A319-100	7	13,1	15	14
2	Airbus A320-200	23	6,6	21,1	14,2
3	Airbus A321-100	3	23,0	23,2	23,1
4	Airbus A321-200	3	17,9	20,2	19
5	Embraer ERJ-195LR	17	6,6	9,4	8,2
6	Bombardier DHC-8-400	18	8,6	20,5	14,5

No.	Aircraft type	Number of aircraft, pcs	Aircraft age, years		Average age of aircraft type, years
			Min	Max	
7	Boeing 777-200	6	12	21,5	16,5
8	Boeing 767-300ER	6	18,3	27,4	23

Austrian Airlines continues a successful development of passenger traffic. The passenger traffic, estimated on the basis of revenue passenger-kilometres (RPK), has increased by 8.9% in comparison with January 2018. Flight utilization rate has averaged to 70.2%, having increased by 0.5 percentage points. The number of flights operated by Austrian Airlines in January 2019 has increased by 4.4%.

AVI.1.7 Turkish Airlines

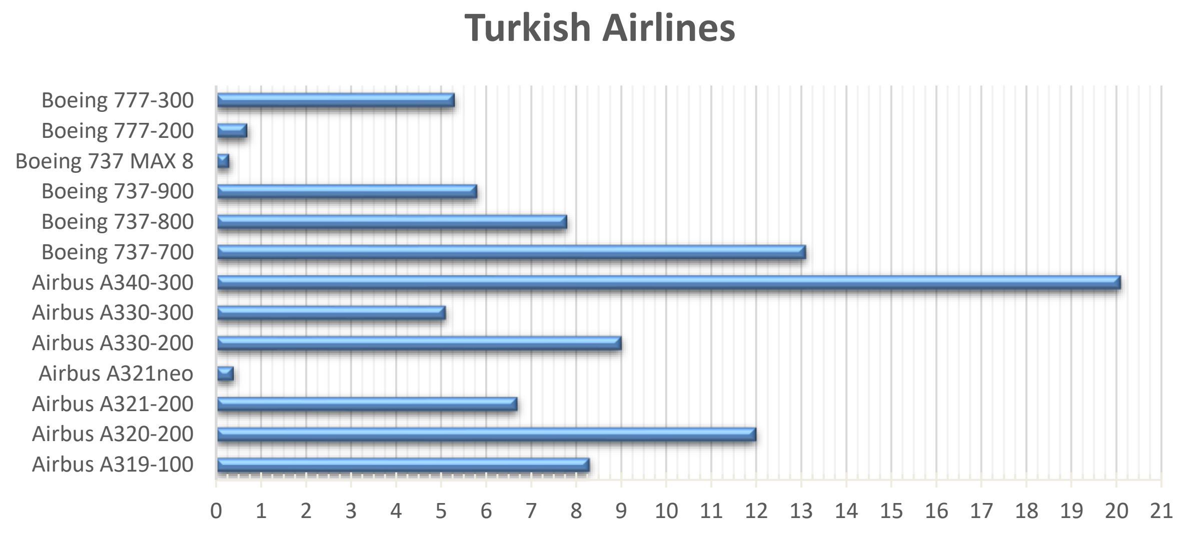
Turkish Airlines is a national air carrier of Turkey. Table 11, Figure 100 and Figure 99 display information about the Turkish Airlines fleet, the number and the average age of the aircraft. **Error! Reference source not found.**



	Airbus A319-100	Airbus A320-200	Airbus A321-200	Airbus A321neo	Airbus A330-200	Airbus A330-300	Airbus A340-300	Boeing 737-700	Boeing 737-800	Boeing 737-900	Boeing 737 MAX 8	Boeing 777-200	Boeing 777-300
Turkish Airlines	7	18	68	2	28	37	3	1	63	15	8	5	33

Table 11. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	7	8,3	-
2	Airbus A320-200	18	12	-
3	Airbus A321-200	68	6,7	-
4	Airbus A321neo	2	0,4	91
5	Airbus A330-200	28	9	-
6	Airbus A330-300	37	5,1	-
7	Airbus A340-300	3	20,1	-
8	Boeing 737-700	1	13,1	-
9	Boeing 737-800	63	7,8	-
10	Boeing 737-900	15	5,8	-
11	Boeing 737 MAX 8	8	0,3	65
12	Boeing 777-200	5	0,7	-
13	Boeing 777-300	33	5,3	-
14	Airbus A350-900	-	-	25
15	Boeing 737 MAX 9	-	-	10
16	Boeing 787-9	-	-	25



	Airbus A319-100	Airbus A320-200	Airbus A321-200	Airbus A321neo	Airbus A330-200	Airbus A330-300	Airbus A340-300	Boeing 737-700	Boeing 737-800	Boeing 737-900	Boeing 737 MAX 8	Boeing 777-200	Boeing 777-300
Turkish Airlines	8.3	12	6.7	0.4	9	5.1	20.1	13.1	7.8	5.8	0.3	0.7	5.3

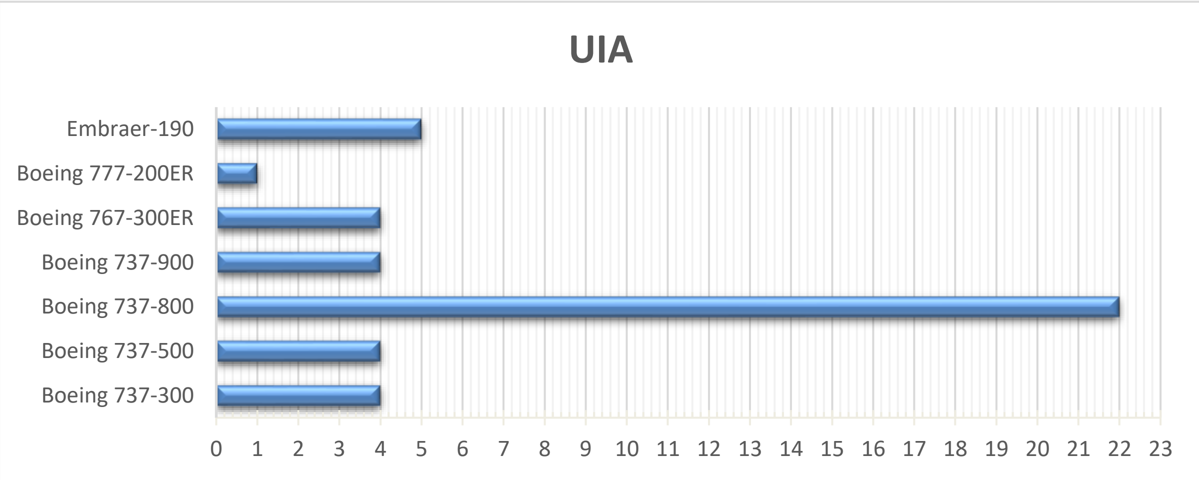
Figure 99. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 10 years. Airbus A321neo deliveries have begun in 2018 and will last until 2023. Also in 2018, deliveries of the Boeing 737MAX8 have begun and will last until 2022. 10 737MAX9s will be delivered from 2019 to 2020 [108]–[111].

AVI.2 CIS airlines

AVI.2.1 Ukraine International Airlines.

Basically, the airline fleet is filled with short- and medium-haul aircraft types. In general, the airline fleet has increased by 35 aircraft over the past 10 years. The airline operates regular and charter flights to 80 destinations. These include 10 destinations within Ukraine, as well as international flights to 24 countries in Europe, 3 countries in Africa, 4 countries in Central Asia, 8 countries in Western Asia, 1 country in Eastern Asia and 1 country in North America. In addition, the company has concluded code-sharing agreements with 13 other airlines. Figure 102. Number of aircraft in the airline fleet



	Boeing 737-300	Boeing 737-500	Boeing 737-800	Boeing 737-900	Boeing 767-300ER	Boeing 777-200ER	Embraer-190
МАУ	4	4	22	4	4	1	5

Table 12, Figure 102 and Figure 100 display information about the UIA fleet, the number and the average age of the aircraft.

Figure 102. Number of aircraft in the airline fleet

Table 12. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years
1	Boeing 737-300	4	23,5
2	Boeing 737-500	4	26,8
3	Boeing 737-800	22	11,3
4	Boeing 737-900	4	8
5	Boeing 767-300ER	4	27
6	Boeing 777-200ER	1	18
7	Embraer 190	5	6,4

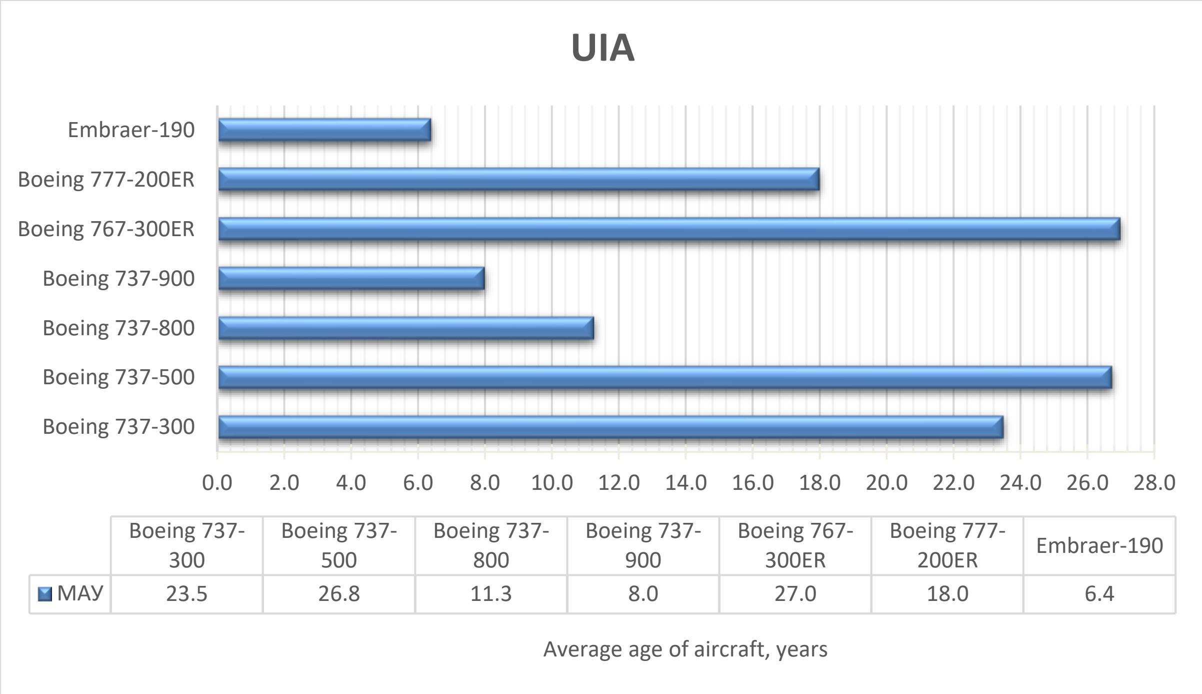


Figure 100. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 17 years. Analysing the average age of the fleet, we can conclude that the company needs to replace the Boeing 767-300ER and Boeing 737-500 fleet in the next 3 years [112], [113].

AVI.2.2 Aeroflot airline

Aeroflot Russian Airlines has the status of a national carrier of Russia and is the largest airline in the country. The company fleet includes modern airliners of Russian and foreign production, and the flight geography covers routes to 52 countries of the world. Out of 146 destinations, 52 are located in Russia, 16 in the CIS, 4 in the Middle East, 5 in America, 13 in Asia, 55 in Europe, 1 in Africa. Table 13, Figure 104 and Figure provide information on the Aeroflot fleet, the number and the average age of the aircraft. **Error! Reference source not found.**

Table 13. Airline fleet, number and age of the aircraft

No.	Aircraft type	Aircraft age, years		Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
		Min	Max			
1	SuperJet 100-95	1	6	48	3.5	2
2	A330	7	11	22	8.6	-
3	A320-214	1	16	80	5.9	1

No.	Aircraft type	Aircraft age, years		Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
		Min	Max			
4	A321-211	1	10	37	4.1	2
5	Boeing 737-800	1	6	47	2.8	5
6	Boeing 777-300ER	1	7	17	4.5	5
7	Airbus A350-900	-	-	-	-	28
8	Иркут MC-21-300	-	-	-	-	50

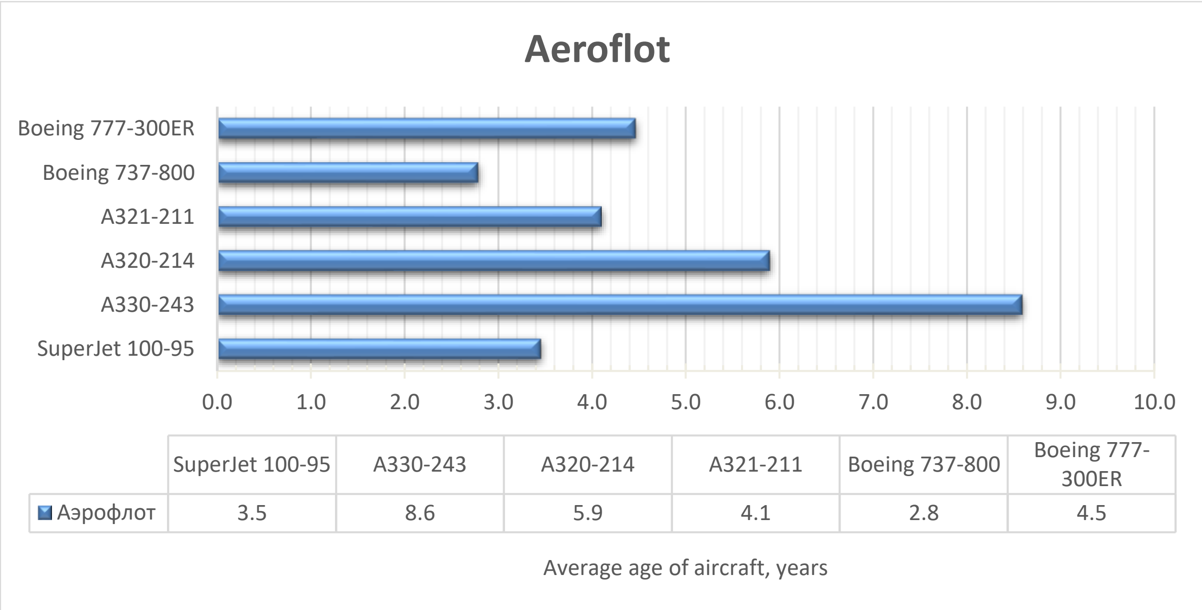


Figure 105. The average age of aircraft type in the airline fleet

Aeroflot has 251 airliners on its balance sheet - Airbus A320, A330, Boeing 737, Boeing 777 and Superjet 100 (SSJ100) aircraft.

Russian passenger aircraft of the new generation Superjet 100 has been entering the Aeroflot air fleet since June 2011. The airline expects 28 Airbus A350-900s in the period from 2019 to 2023, as evidenced by Aeroflot financial statements for 6 months of 2017. The airline has a young fleet, and in the near future does not require updating [114]–[117].

AVI.2.3 AZUR Air airline

AZUR Air is a Russian airline, one of the largest charter carriers in the country. AZUR Air performs transportation in international directions, providing the needs of the largest Russian tour operators. During the year, AZUR Air operates flights from forty Russian cities to twenty-nine international tourist destinations. Table 14. Figure 106 and Figure display the information about the AZUR Air fleet, the number and the average age of the aircraft.

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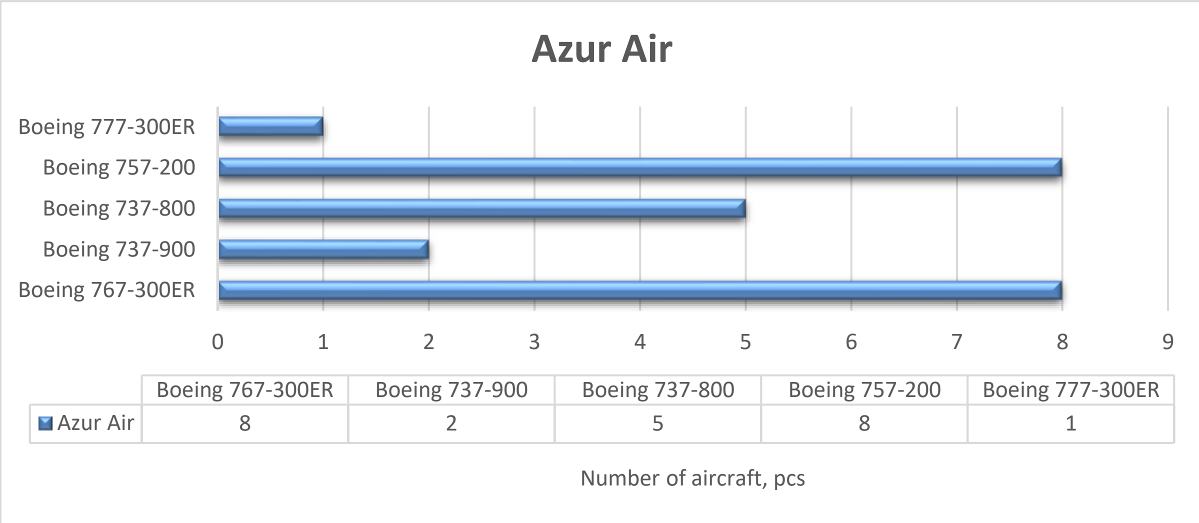

Table 14. Airline fleet, number and age of the aircraft

No.	Aircraft type	Aircraft age, years		Number of aircraft, pcs	Average age of aircraft type, years
		Min	Max		
1	Boeing 767-300ER	20	28	8	25,0
2	Boeing 737-900	12	12	2	12
3	Boeing 737-800	18	21	5	19,6
4	Boeing 757-200	17	26	8	20,8
5	Boeing 777-300ER	-	14	1	14

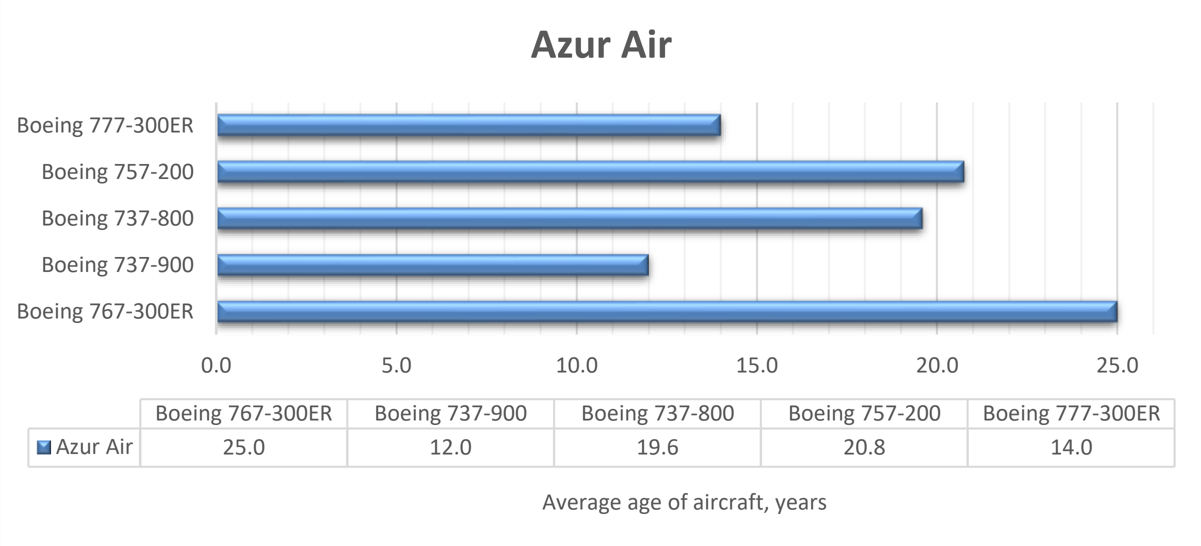

Figure 107. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 18 years. In the near future, the airline will have to update the Boeing 767-300ER fleet, since the average age of this type of aircraft is 25 years [116], [118], [119].

AVI.2.4 Pegas Fly (Ikar) airline

LLC "Aircompany" Ikar" is a Russian airline based in Krasnoyarsk. Currently, our airline carries out regular and charter transportation of passengers, baggage and cargo both on domestic and international routes. Table 15, Figure and Figure display information about the Pegas Fly fleet, the number and the average age of the aircraft.

Table 15. Airline fleet, number and age of the aircraft

No.	Aircraft type	Aircraft age, years		Number of aircraft, pcs	Average age of aircraft type, years
		Min	Max		
1	Boeing 767-300ER	19	23	6	20,7
2	Boeing 737-800	13	18	4	15,5
3	Embraer 190LR	8	11	6	9,5

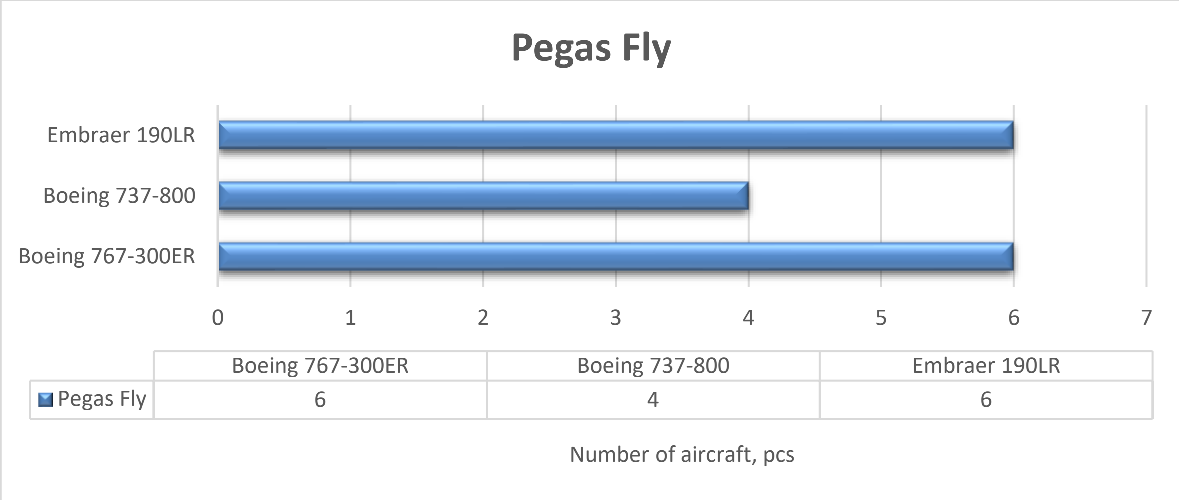

Figure 108. Number of aircraft in the airline fleet

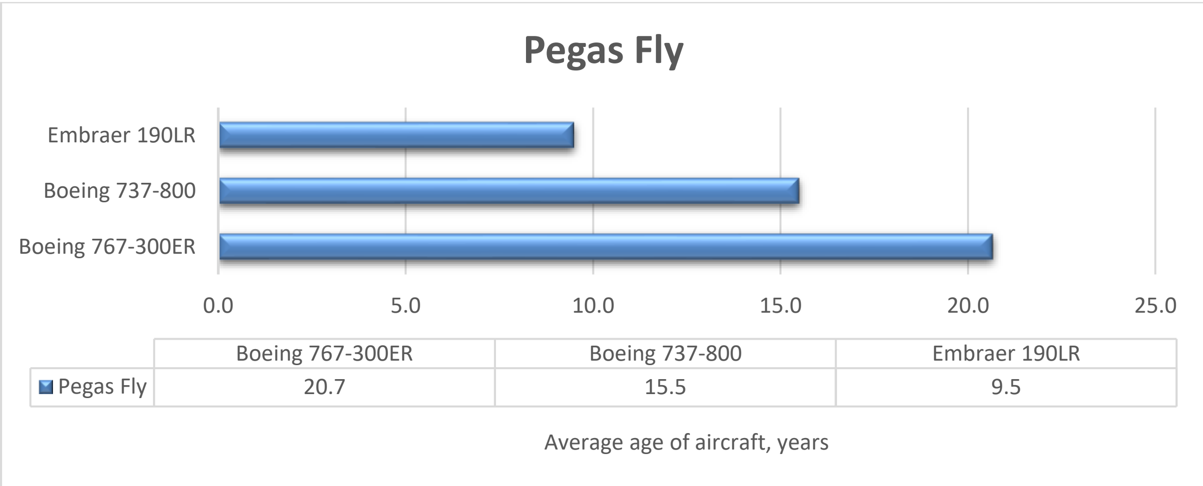

Figure 109. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 16 years. The airline fleet also included four Boeing 757-200 aircraft decommissioned by the company at the end of 2014, as well as three Boeing 767-300 aircraft decommissioned by the company in 2016 [120], [121].

AVI.2.5 Royal Flight airline

Royal Flight is a Russian airline based at Sheremetyevo Airport. Table 16, Figure 110 and Figure 111 display information about the Royal Flight fleet, the number and the average age of the aircraft.

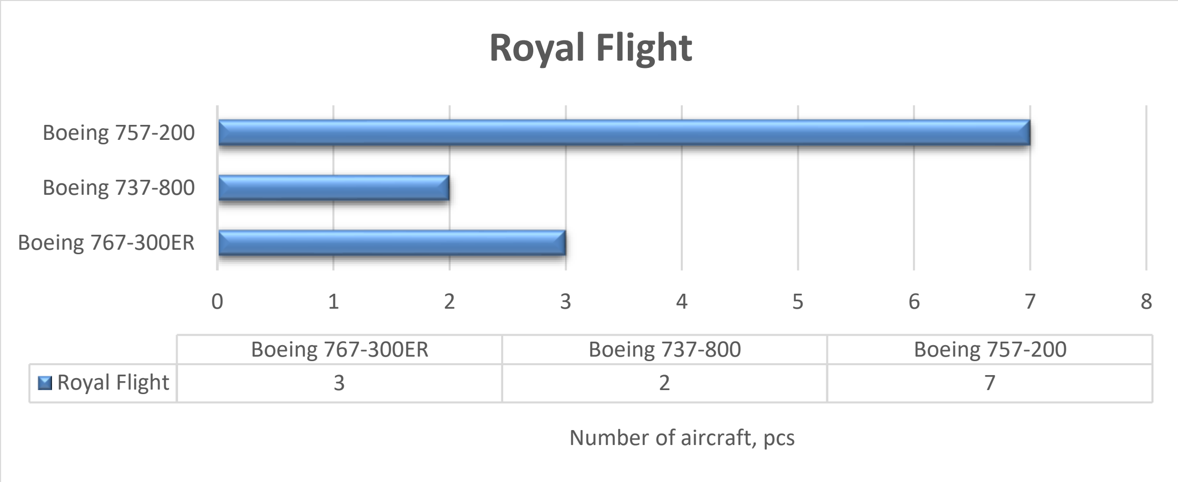

Figure 110. Number of aircraft in the airline fleet

Table 16. Airline fleet, number and age of the aircraft

No.	Aircraft type	Aircraft age, years		Number of aircraft, pcs	Average age of aircraft type, years
		Min	Max		
1	Boeing 767-300ER	21	23	3	21,7
2	Boeing 737-800	12	17	2	14,5
3	Boeing 757-200	18	21	7	19,9

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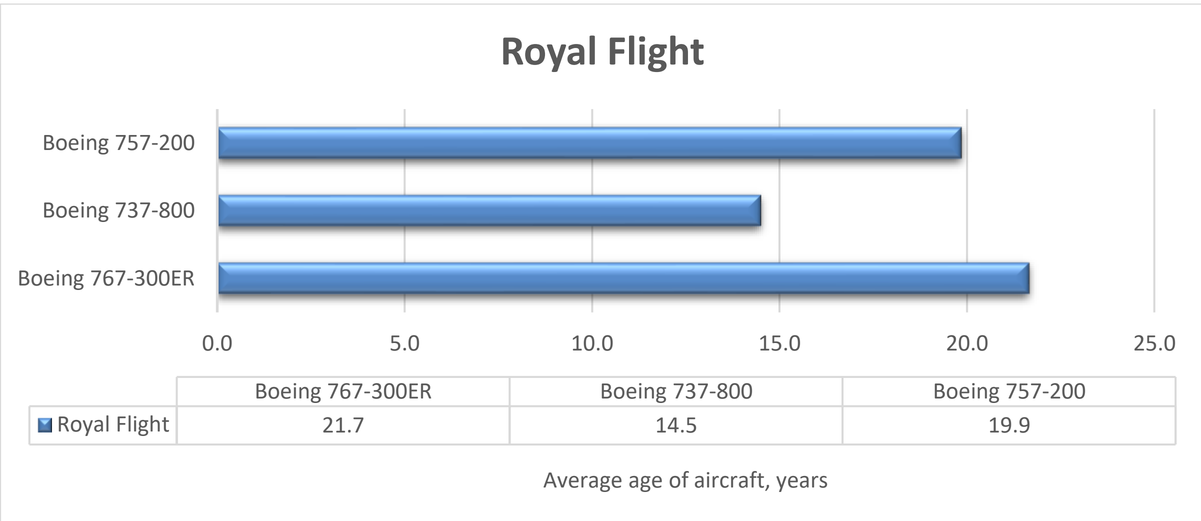


Figure 101. The average age of aircraft type in the airline fleet

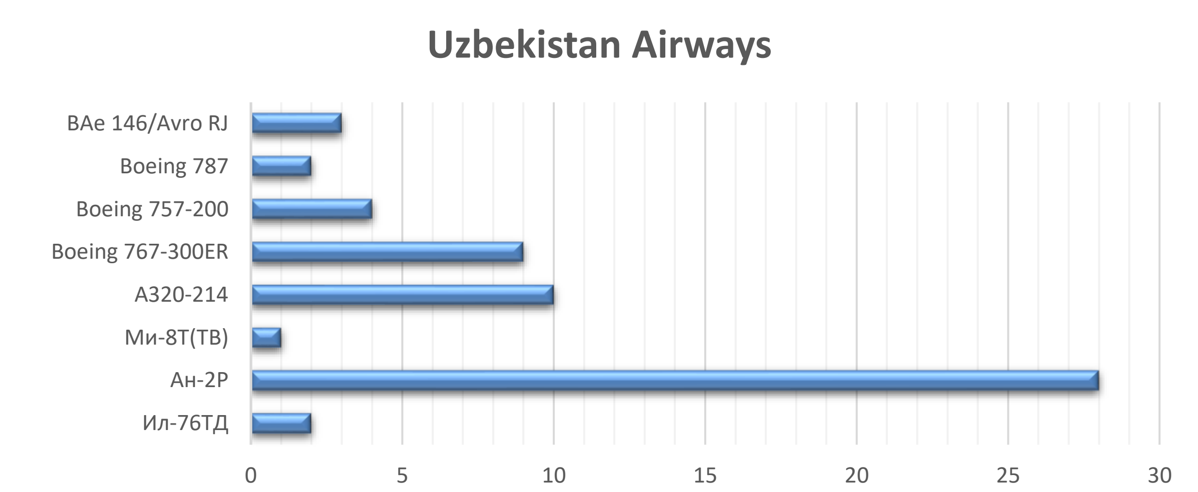
The average age of the airline fleet is about 17 years. The oldest aircraft is 23 years old (Boeing 767-300ER) [116], [122], [123].

AVI.2.6 Uzbekistan Airways airline

Uzbekistan Airways is a national air carrier of Uzbekistan. Every year, the number of passengers carried by Uzbekistan Airways is growing by 10-15% and has already amounted to more than 3 million people. The route network of the company is about 60 destinations, which include domestic and international flights to Europe, Asia, and North America. Representative offices of the airline are located in more than 25 countries of the world. Also, the airline owns 11 airports within the country, 6 of which are international and can host aircraft from other countries. Uzbekistan Airways is one of the largest airlines in the post-Soviet space (not counting Russian airline companies). Table 17, Figure 112 and Figure 113 display information about the fleet of Uzbekistan Airways, the number and the average age of the aircraft.

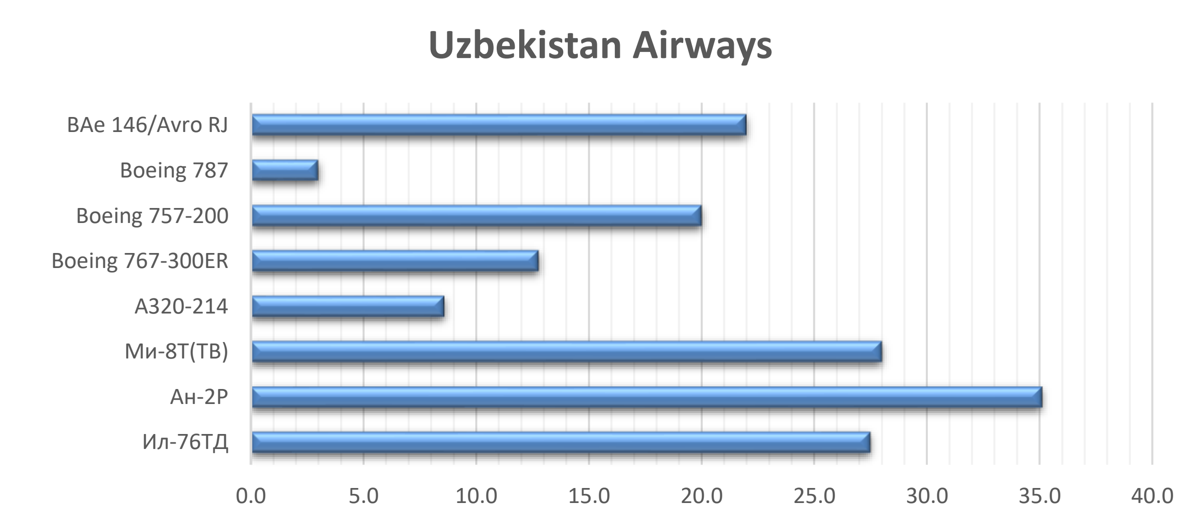
Table 17. Airline fleet, number and age of the aircraft

No.	Aircraft type	Age, years		Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
		Min	Max			
1	Ил-76ТД	26	29	2	27,5	-
2	Ан-2П	28	51	28	35,1	-
3	Ми-8Т(ТВ)	-	28	1	28,0	-
4	A320-214	8	9	10	8,6	-
5	Boeing 767-300ER	6	23	9	12,8	-
6	Boeing 757-200	20	20	4	20,0	-
7	Boeing 787	1	2	4	1,5	-
8	BAe 146/Avro RJ	22	22	3	22,0	-
9	Airbus A320neo	-	-	-	-	2
10	Boeing 787-9	-	-	-	-	3



	Ил-76ТД	Ан-2Р	Ми-8Т(ТВ)	A320-214	Boeing 767-300ER	Boeing 757-200	Boeing 787	BAe 146/Avro RJ
Uzbekistan Airways	2	28	1	10	9	4	2	3

Figure 112. Number of aircraft in the airline fleet



	Ил-76ТД	Ан-2Р	Ми-8Т(ТВ)	A320-214	Boeing 767-300ER	Boeing 757-200	Boeing 787	BAe 146/Avro RJ
Uzbekistan Airways	27.5	35.1	28.0	8.6	12.8	20.0	3.0	22.0

Figure 113. The average age of aircraft type in the airline fleet

The average age of the passenger fleet is about 19 years. The delivery of 2 Airbus A320neo is expected in January 2019 [124]–[126].

AVI.3 Middle East airlines

Airlines in the Middle East have maximized their geographical advantage to attract global demand for air travel. Over the past 20 years, both passenger demand and freight demand have doubled. In particular, Emirates Airlines, Etihad Airways and Qatar Airways have expanded networks of routes from Dubai, Abu Dhabi and Doha around the world and have reached a large transit demand. Therefore, these airlines need large wide-bodied aircraft with longer range. In addition, their purchasing capacity allows them to have a huge impact on aircraft manufacturers. Wide-body aircraft will account for 60% of new shipments of passenger aircraft[91].

AVI.3.1 Emirates airline

Emirates is one of the largest airlines in the world. Emirates aircraft operate regular flights around the world. Table 18, Figure and Figure 115 display information about the Emirates fleet, the number and the average age of the aircraft.**Error! Reference source not found.**

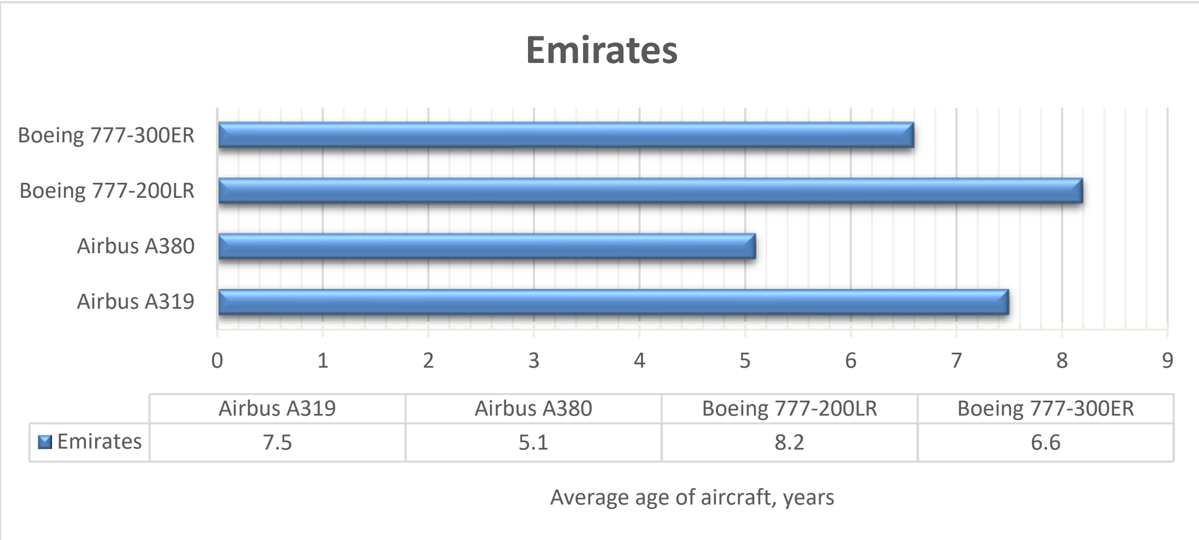


Table 18. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319	1	7,5	–
2	Airbus A380	109	5,1	14
3	Airbus A330 – 900	–	–	40
4	Airbus A350	–	–	30
5	Boeing 777-200LR	10	8,2	–

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
6	Boeing 777-300ER	139	6,6	–
7	Boeing 777-8	–	–	35
8	Boeing 777-9	–	–	115

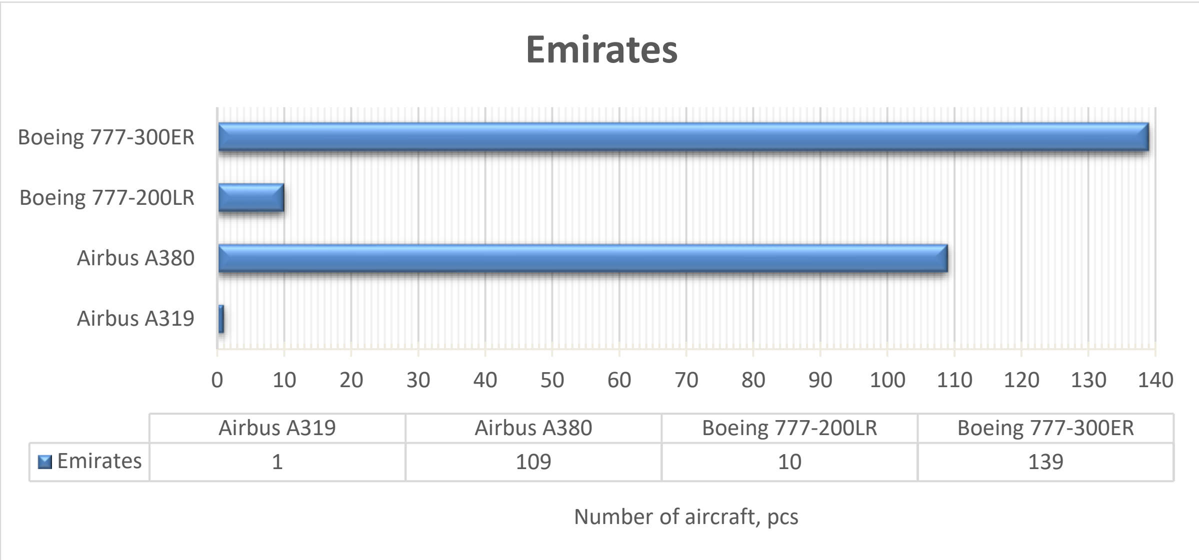


Figure 115. Number of aircraft in the airline fleet

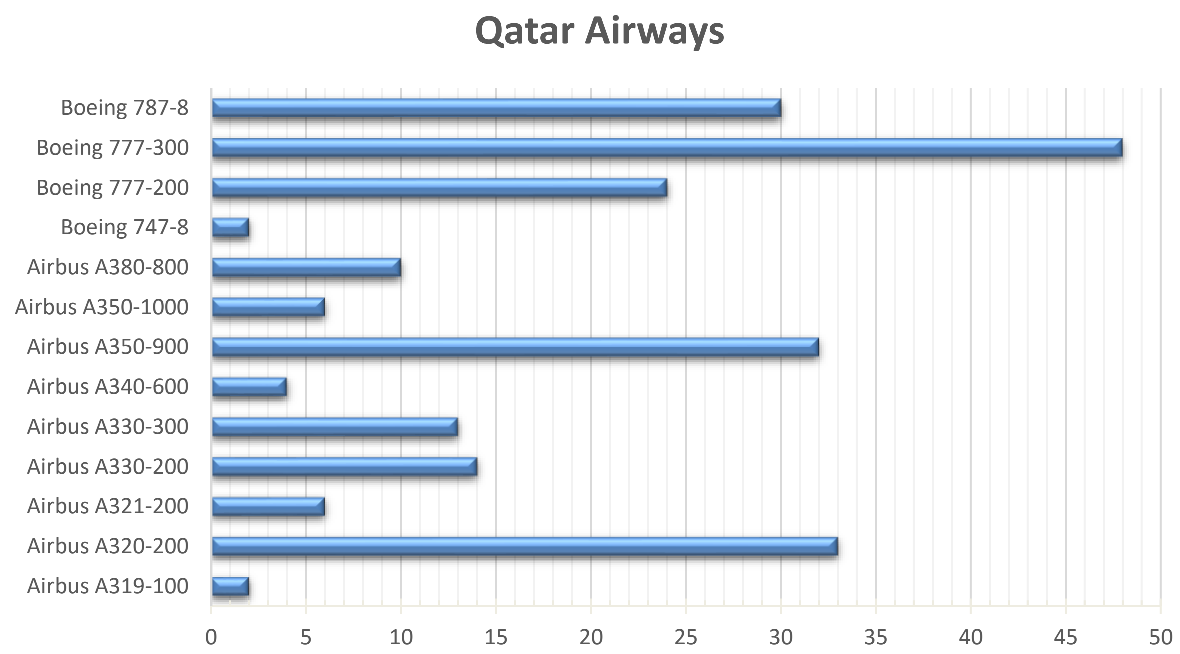
The average age of the airline fleet is about 7 years. Initially, the airline planned to update the fleet with new Airbus A380 to be delivered by 2027 - 2029. But according to Airbus [127] Emirates airline has changed the initial order. According to new data, Airbus will deliver 14 A380s by 2021 and the total number of A380s will be 123, rather than 162, as previously planned. Having cut an order for the A380, Emirates decided to increase its fleet with Airbus newest generation, flexible widebody aircraft, ordering 40 A330-900 and 30 A350-900 aircraft. Delivery terms are not specified. Emirates also ordered the delivery of 150 Boeing 777 aircraft [128]–[133].

AVI.3.2 Qatar Airways airline

Qatar Airways is the country's national airline. The airline flies to 101 destinations worldwide. Table 19, Figure and Figure display information about the Qatar Airways fleet, the number and the average age of the aircraft.

Table 19. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	2	15,6	-
2	Airbus A320-200	33	7,8	-
3	Airbus A321-200	6	11,3	-
4	Airbus A330-200	14	8,7	-
5	Airbus A330-300	13	12,7	-
6	Airbus A340-600	4	12,6	-
7	Airbus A350-900	32	2,1	14
8	Airbus A350-1000	6	0,6	35
9	Airbus A380-800	10	3,6	-
10	Boeing 747-8	2	4	-
11	Boeing 777-200	24	6	-
12	Boeing 777-300	48	5,2	7
13	Boeing 787-8	30	4,6	-
14	Airbus A321neo	-	-	50
15	Boeing 777-8X	-	-	10
16	Boeing 777-9X	-	-	50
17	Boeing 787-9	-	-	30



	Airbus A319-100	Airbus A320-200	Airbus A321-200	Airbus A330-200	Airbus A330-300	Airbus A340-600	Airbus A350-900	Airbus A350-1000	Airbus A380-800	Boeing 747-8	Boeing 777-200	Boeing 777-300	Boeing 787-8
Qatar Airways	2	33	6	14	13	4	32	6	10	2	24	48	30

Number of aircraft, pcs

Figure 116. Number of aircraft in the airline fleet

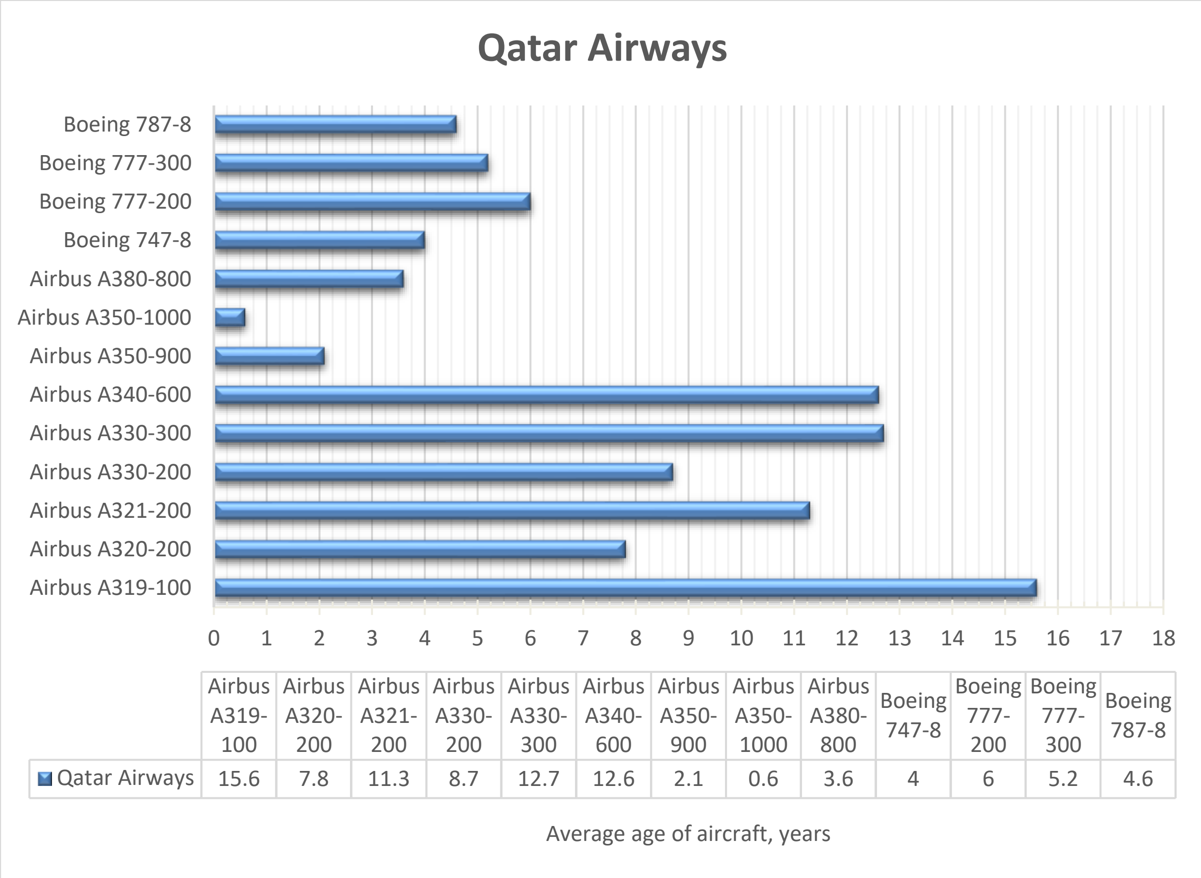


Figure 117. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 9 years. The company has a young fleet and there is no need to purchase new aircraft in the next few years [134]–[136].

AVI.3.3 Etihad Airways airline

In 2018, Etihad Airways operated the aircraft listed in Table 20. The airline routes make up more than 80 destinations to different cities of the world.

Table 20. Airline fleet and aircraft orders[137]

Aircraft type	Number of aircraft, pcs	Order by 2020	Option
Airbus A320-200	22		18
Airbus A321-200	10	-	-
Airbus A321neo	-	26	-
Airbus A330-200	16	-	-

Aircraft type	Number of aircraft, pcs	Order by 2020	Option
Airbus A330-300	4	-	-
Airbus A350-900	-	40	-
Airbus A350-1000	-	22	15
Airbus A380-800	10	-	5
Boeing 777-300ER	19	-	12
Boeing 777-8	-	8	-
Boeing 777-9	-	17	-
Boeing 787-9	22	20	25
Boeing 787-10	4	26	12

AVI.4 Asia Pacific region airlines

China and India have the most massive domestic markets and strong demand for narrow-body aircraft. The projected market for the supply of new aircraft reaches 61% over the past 7 years. China, along with Europe and North America, will be one of the three main markets that will lead the global demand for air travel in the next 10 years. Although at present, China is widely using B737 and A320, it is expected that in the near future there will be a transition to the purchase of in-house aircraft in the process of foreign technologies mastering.

Japan intends to commission its MRJ regional aircraft designed by the Japanese company Mitsubishi Aircraft Corporation. However, as of July 2018, the flight test program of the aircraft was not fully implemented due to technical problems. Airlines in Vietnam and Australia are purchasing aircraft from leading global manufacturers[91].

Air China is the national carrier of China. Table 21 shows general information about the airline fleet. Figure and Figure 102 display information about the number and average age of the aircraft.

According to the analysis, the average age of the airline fleet is about 12 years. Airbus A320neo deliveries will last until 2020. In 2018, the deliveries of the Airbus A321neo and Airbus A350-900 began. New Boeing 747-8I will replace 747-400 once they are decommissioned. Also in 2018, the deliveries of Boeing 737MAX8 began [138]–[142].

AVI.4.1 China Southern Airlines

China Southern Airlines is an air carrier based in Guangzhou, Guangdong Province, China. It performs local, regional and international flights. It is the largest Asian airline in terms of fleet number, the largest air carrier in Asia, the 7th largest airline in the world for local passenger transportation, the 7th largest airline in the world in terms of passenger traffic in passenger-kilometres. Table 22, Figure and Figure display information about the China Southern fleet, the number and the average age of the aircraft.

The average age of the airline fleet is about 8 years. The airline has ordered 161 Airbus airplanes of various types. The company has ordered 20 Airbus A350-900s and the deliveries are expected from 2019 to 2022. The airline has ordered 105 different types of aircraft from Boeing. The deliveries of 62 ordered Boeing 737MAX8s began in 2017. Also starting from 2018, the deliveries of 13 Boeing 787-9s have begun and will last until 2020[143]–[145].

AVI.4.2 China Eastern Airlines

China Eastern Airlines is a major Chinese air carrier, one of the top five leaders in the world in terms of the number of passengers carried. The fleet is considered one of the most representative in the world. The company's headquarters are located in Shanghai. China

Eastern Airlines delivers customers to major cities and countries around the world. Table 23, Figure 103 and Figure 104 display information about the China Eastern Airlines fleet, the number and average age of the aircraft.

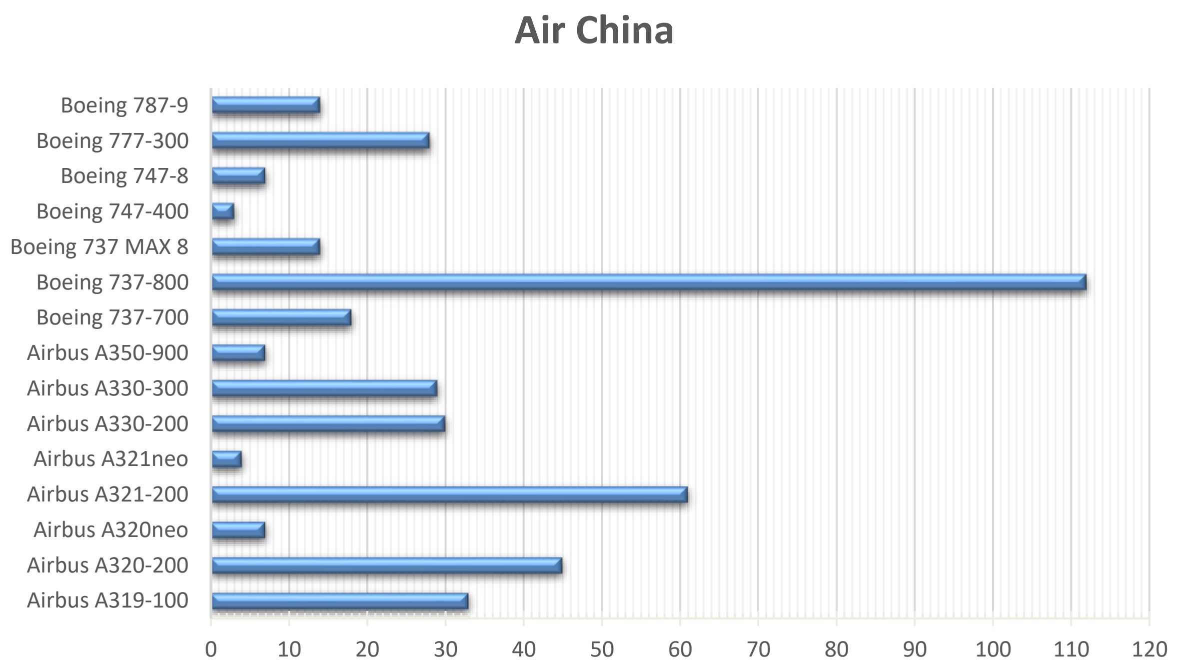
The average age of the airline fleet is about 4 years. According to the official website, the airline has ordered 49 aircraft of various types. The largest order of Boeing 787-8 type for 15 aircraft has been signed by the airline and is awaiting delivery soon [146]–[148].

AVI.4.3 Air China airline

Table 21. Air China fleet

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	33	12,7	-
2	Airbus A320-200	45	6	-
3	Airbus A320neo	7	0,7	-
4	Airbus A321-200	61	7	-
5	Airbus A321neo	4	0,3	11

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
6	Airbus A330-200	30	9,9	-
7	Airbus A330-300	29	5	-
8	Airbus A350-900	7	0,5	6
9	Boeing 737-700	18	12,3	-
10	Boeing 737-800	112	7	54
11	Boeing 737 MAX 8	14	0,9	33
12	Boeing 747-400	3	22,6	-
13	Boeing 747-8	7	4,2	-
14	Boeing 777-300	28	4,9	-
15	Boeing 787-9	14	2	1
16	Airbus A319-100	33	12,7	-
17	Comac C919	-	-	20



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A321neo	Airbus A330-200	Airbus A330-300	Airbus A350-900	Boeing 737-700	Boeing 737-800	Boeing 737 MAX 8	Boeing 747-400	Boeing 747-8	Boeing 777-300	Boeing 787-9
Air China	33	45	7	61	4	30	29	7	18	112	14	3	7	28	14

Number of aircraft, pcs

Figure 118. Number of aircraft in the airline fleet air China

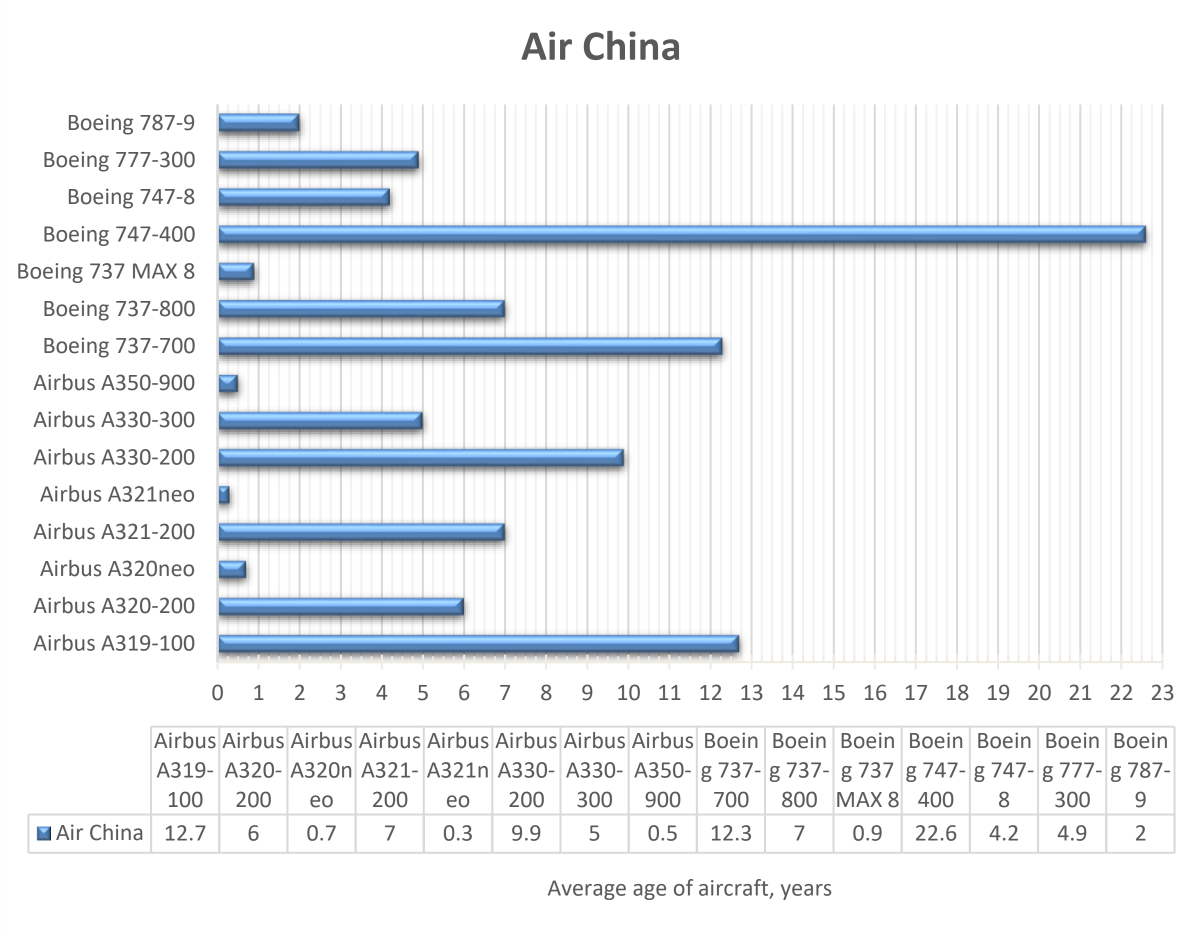
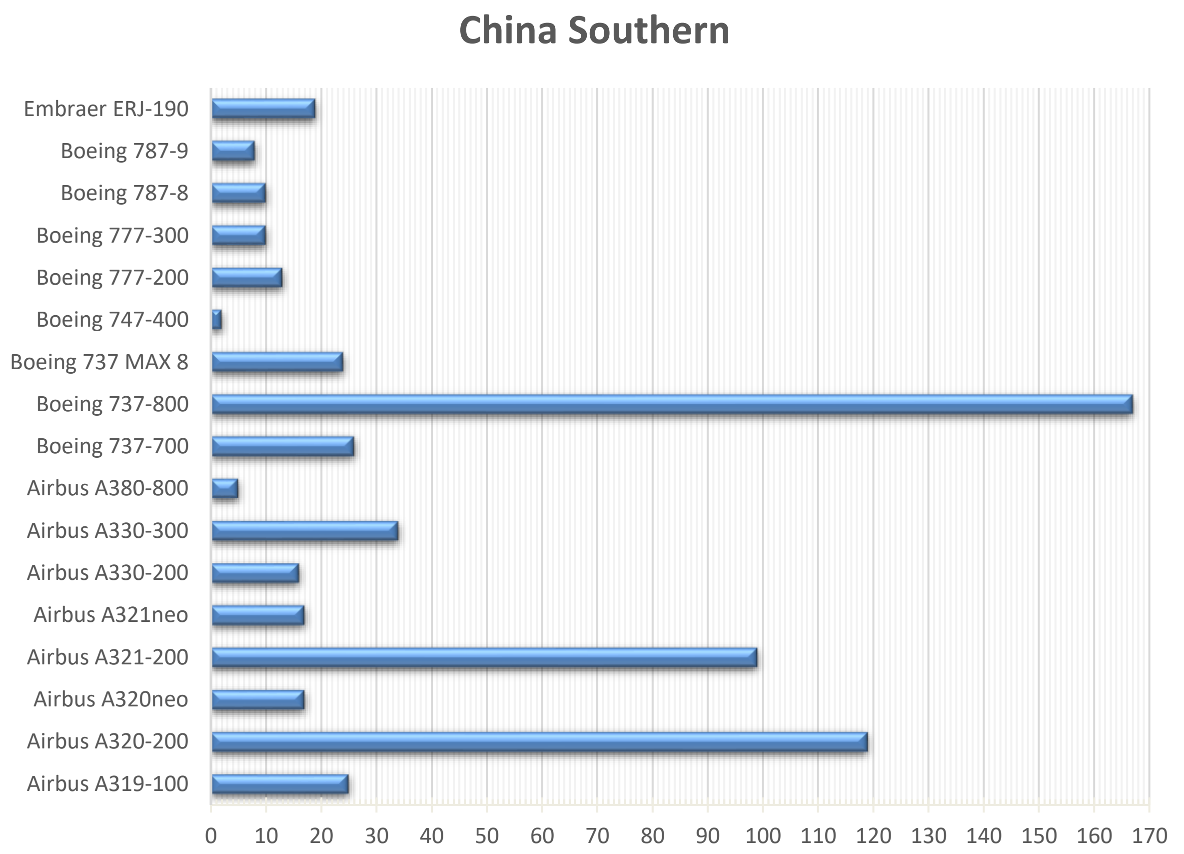


Figure 102. The average age of aircraft in Air China airline

Table 22. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs.
1	Airbus A319-100	25	13,6	-
2	Airbus A320-200	119	9,2	25
3	Airbus A320neo	17	1,1	88
4	Airbus A321-200	99	8	6
5	Airbus A321neo	17	0,6	38
6	Airbus A330-200	16	9,7	-
7	Airbus A330-300	34	4,8	1
8	Airbus A380-800	5	7,3	-

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs.
9	Boeing 737-700	26	11,4	-
10	Boeing 737-800	167	6,1	2
11	Boeing 737 MAX 8	24	0,7	-
12	Boeing 747-400	2	16,7	62
13	Boeing 777-200	13	6,8	
14	Boeing 777-300	10	3,8	8
15	Boeing 787-8	10	5,5	-
16	Boeing 787-9	8	0,6	13
17	Embraer ERJ-190	19	6,9	-
18	Comac C919	-	-	20
19	Airbus A350-900	-	-	20



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A321neo	Airbus A330-200	Airbus A330-300	Airbus A380-800	Boeing 737-700	Boeing 737-800	Boeing 737 MAX 8	Boeing 747-400	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9	Embraer ERJ-190
China Southern	25	119	17	99	17	16	34	5	26	167	24	2	13	10	10	8	19

Number of aircraft, pcs

Figure 120. Number of aircraft in the airline fleet

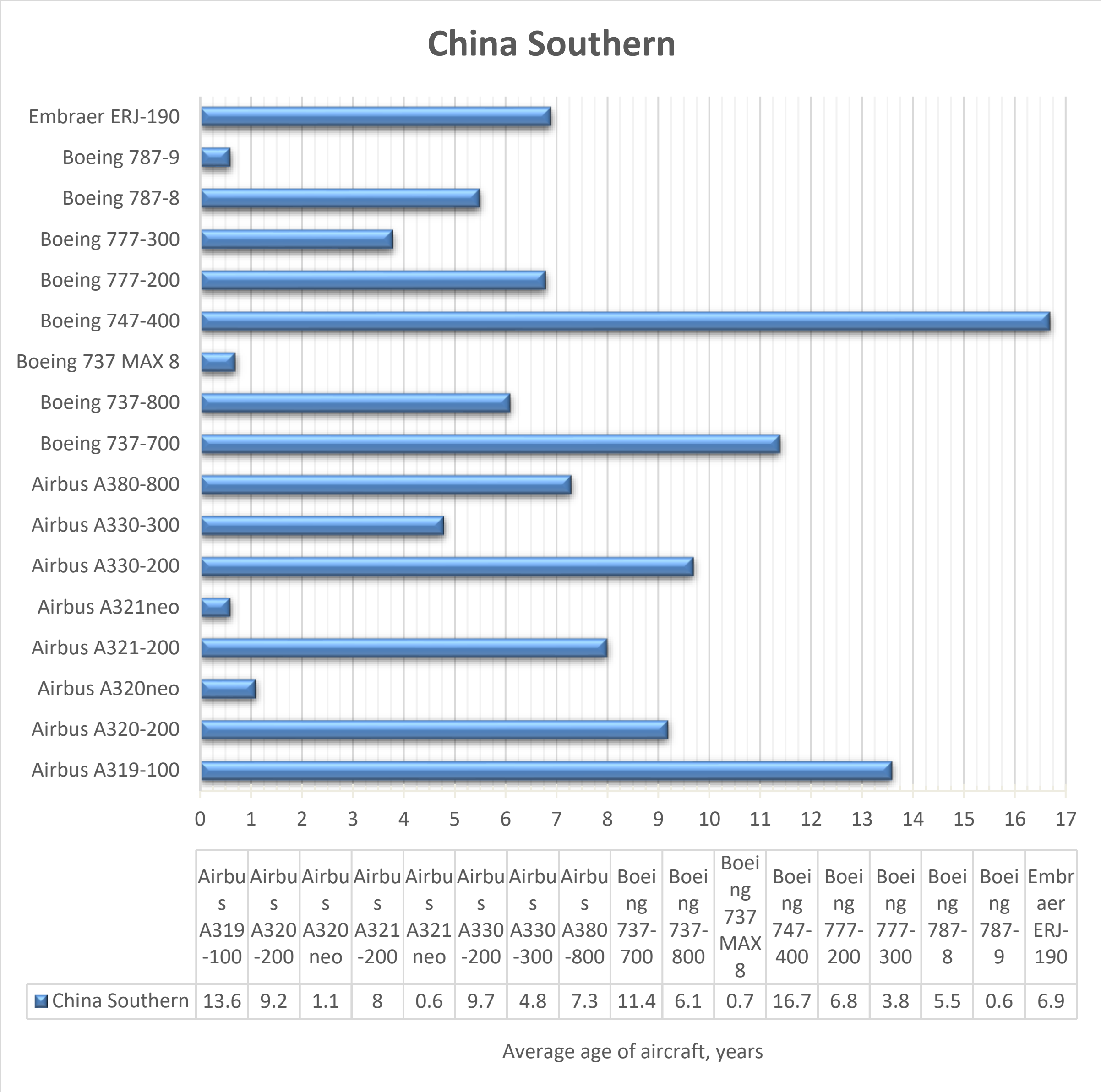
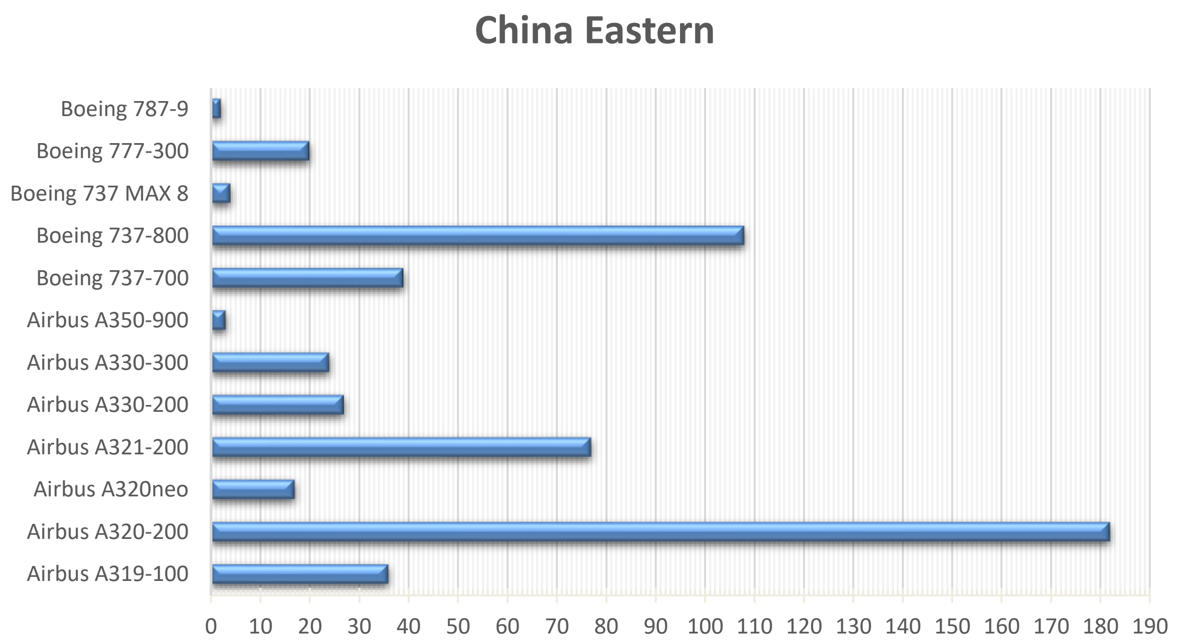


Figure 121. The average age of aircraft type in the airline fleet

Table 23. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	36	5,9	-
2	Airbus A320-200	182	8,2	3
3	Airbus A320neo	17	0,5	3
4	Airbus A321-200	77	5,6	2

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
5	Airbus A330-200	27	5,8	-
6	Airbus A330-300	24	4,1	4
7	Airbus A350-900	3	0,2	-
8	Boeing 737-700	39	9,1	-
9	Boeing 737-800	108	3,8	2
10	Boeing 737 MAX 8	4	1,2	-
11	Boeing 777-300	20	3,1	3
12	Boeing 787-9	2	0,3	-
13	Comac C919	-	-	20
14	Boeing 787-8	-	-	15



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A330-200	Airbus A330-300	Airbus A350-900	Boeing 737-700	Boeing 737-800	Boeing 737 MAX 8	Boeing 777-300	Boeing 787-9
China Eastern	36	182	17	77	27	24	3	39	108	4	20	2

Number of aircraft, pcs

Figure 103. Number of aircraft in the airline fleet

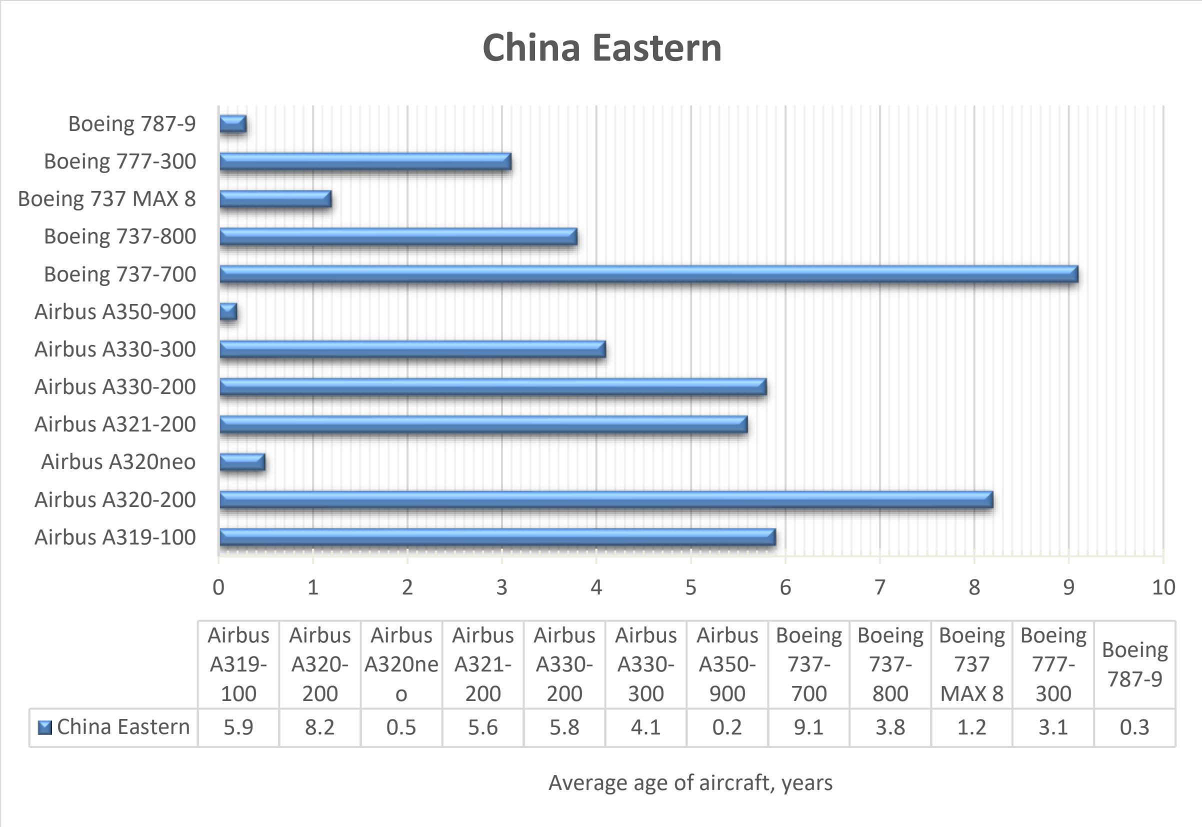


Figure 104. The average age of aircraft type in the airline fleet

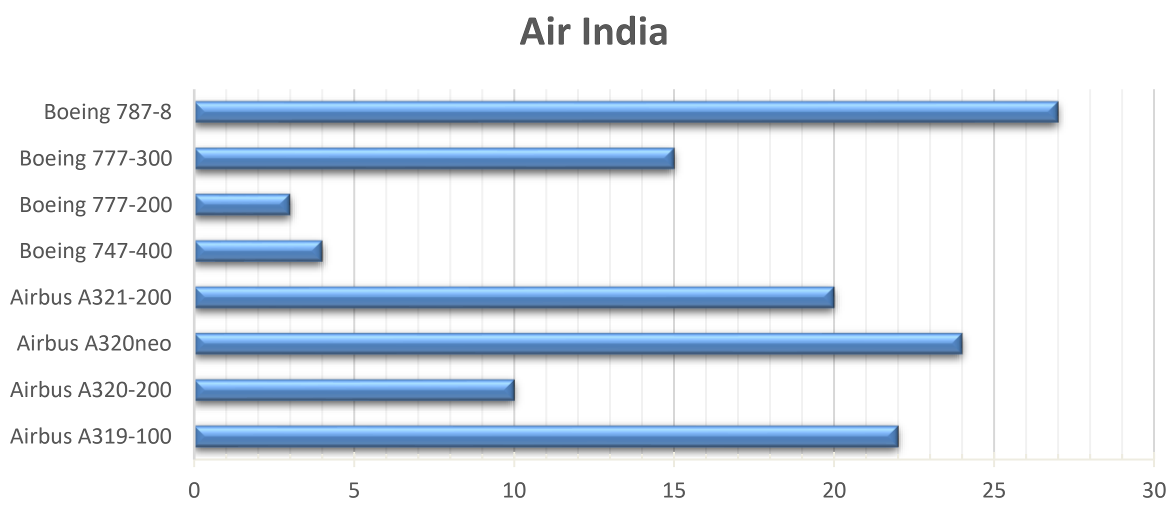
AVI.4.4 Air India airline

Air India Limited airline, the flagship carrier of India, carrying out passenger and cargo air transportation within the country and abroad. Air India has code-sharing agreements with 12 other international airlines, which allows it to fly to 130 airports in the world, including 12 airports in India. On July 11, 2014, Air India became the 27th member of the Star Alliance. Table 24, Figure 105 and Figure 106 display information about the Air India fleet, the number and the average age of the aircraft.

Table 24. Airline fleet, number and age of the aircraft

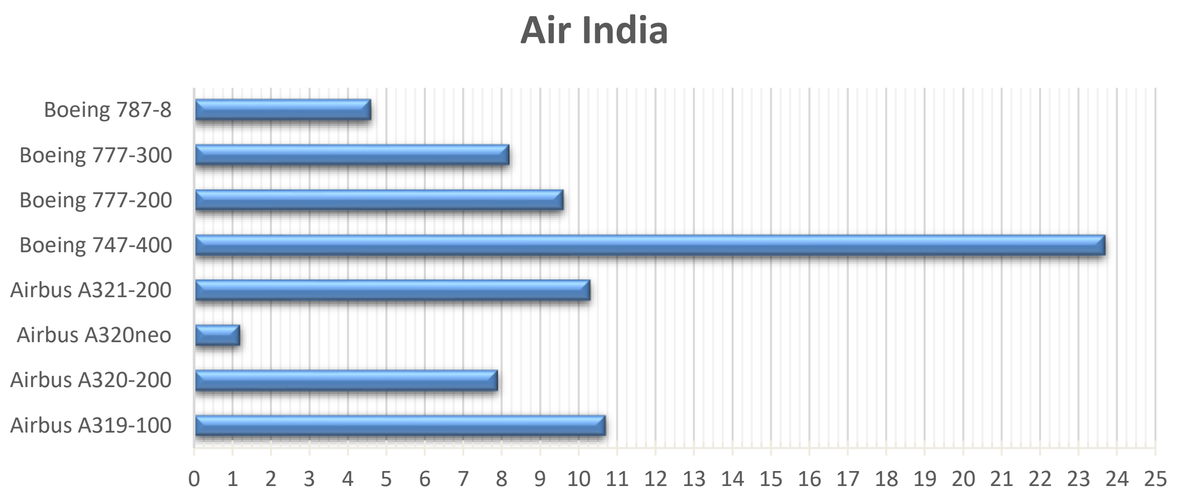
No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	22	10,7	-
2	Airbus A320-200	10	7,9	-
3	Airbus A320neo	24	1,2	1
4	Airbus A321-200	20	10,3	-

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
5	Boeing 747-400	4	23,7	-
6	Boeing 777-200	3	9,6	-
7	Boeing 777-300	15	8,2	-
8	Boeing 787-8	27	4,6	-



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Boeing 747-400	Boeing 777-200	Boeing 777-300	Boeing 787-8
Air India	22	10	24	20	4	3	15	27

Figure 105. Number of aircraft in the airline fleet



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Boeing 747-400	Boeing 777-200	Boeing 777-300	Boeing 787-8
Air India	10.7	7.9	1.2	10.3	23.7	9.6	8.2	4.6

Figure 106. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 12 years. Over the past year, the airline has received 15 new aircraft of various types[149]–[151].

AVI.4.5 Vietnam Airlines

Vietnam Airlines is a Vietnam's national air carrier. Over the last 15 years, the airline has been developing very dynamically, showing an average of 10% of annual growth, and constantly expanding and improving its fleet. The main activity of the company is carrying out of international flights from Vietnam throughout the world, making it one of the largest air transport organizations in the region. Table 25, Figure 107 and Figure 108 display information about the Vietnam Airlines fleet, the number and the average age of the aircraft.

Table 25. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	ATR 72	3	8,5	-
2	Airbus A321-200	57	8,1	-
3	Airbus A321neo	5	0,2	19
4	Airbus A330-200	4	7,4	-
5	Airbus A350-900	12	2,2	2

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
6	Boeing 787-9	11	3	-
7	Boeing 787-10	-	-	8

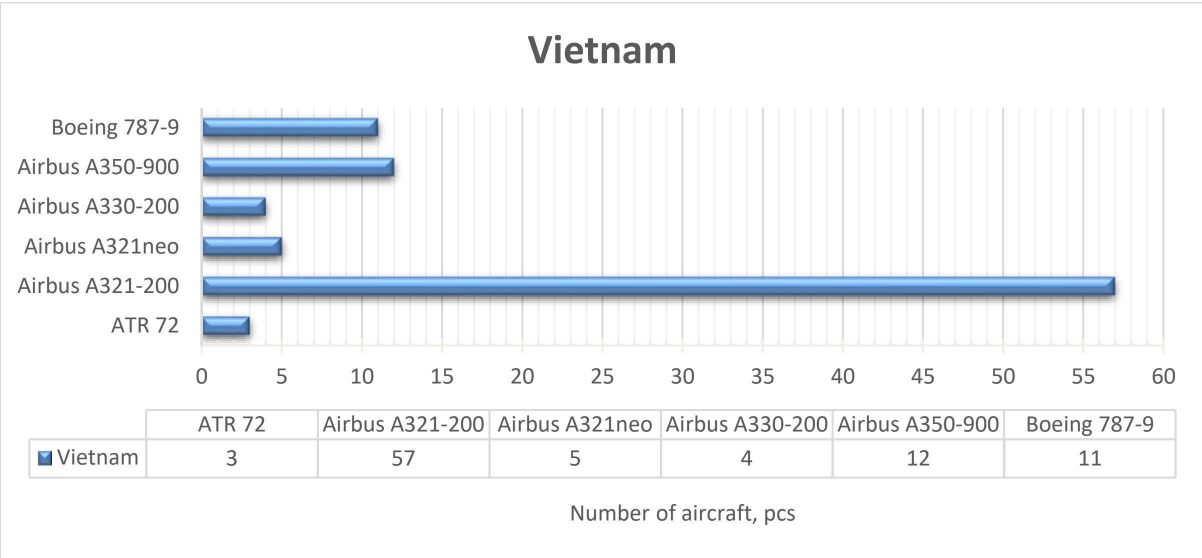


Figure 107. Number of aircraft in the airline fleet

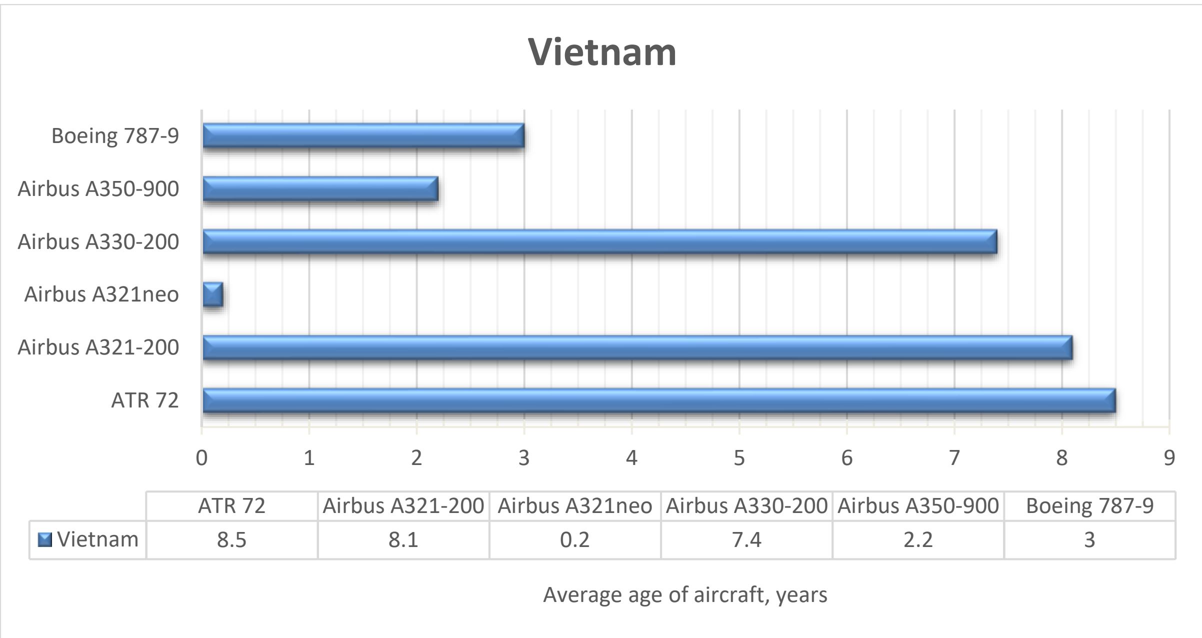


Figure 108. The average age of aircraft type in the airline fleet

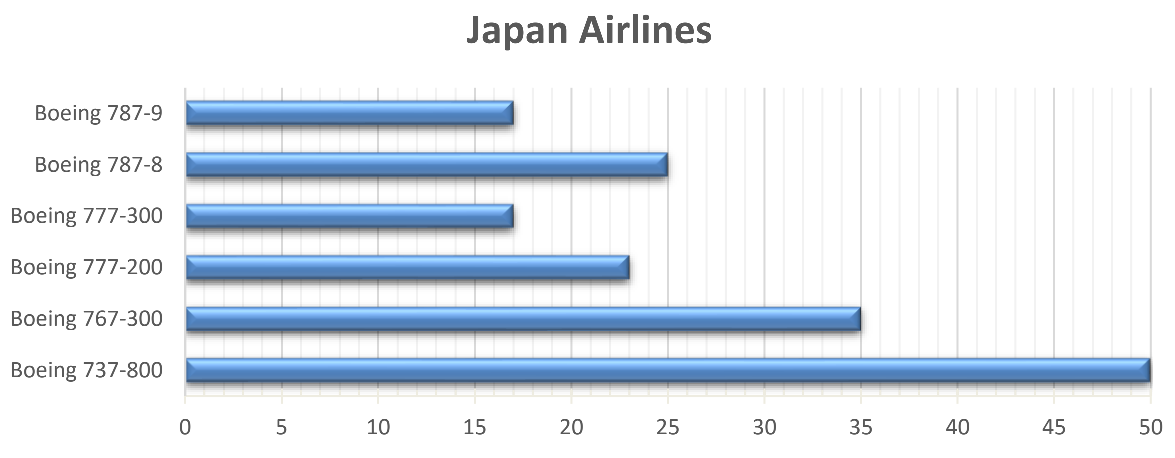
The Vietnam Airlines fleet has an average age of about 5 years. The deliveries of Airbus A321neo aircraft to the company have begun in 2018 and will end in 2019. The deliveries of another 8 ordered Boeing 787-10 are scheduled to begin in 2019 and will last until 2021[152]–[154].

AVI.4.6 Japan Airlines

Japan Airlines is a Japanese national air carrier and one of the largest Asian airlines. Japan Airlines operates a number of domestic and international destinations in Asia, America, Europe and Oceania. Table 26, Figure and Figure display information about the Japan Airlines fleet, the number and the average age of the aircraft.

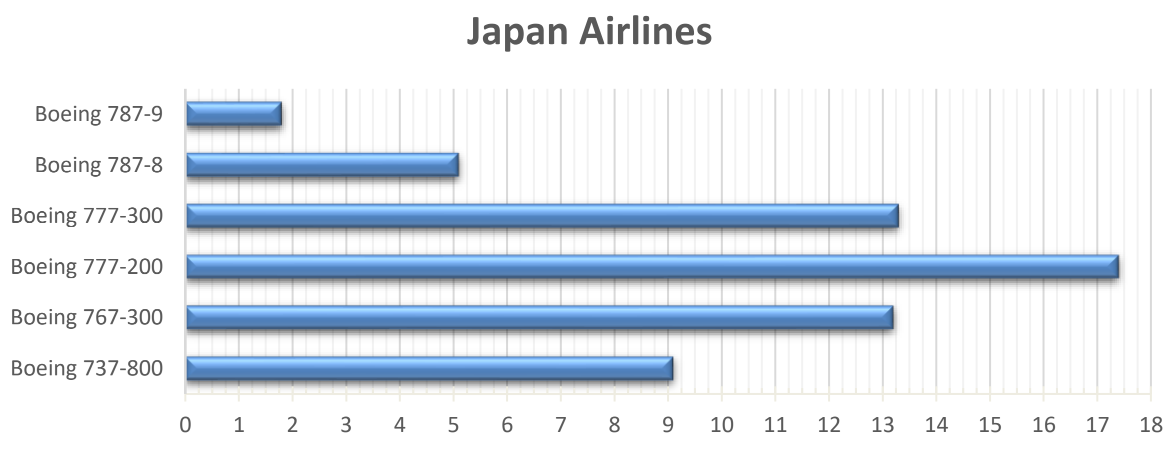
Table 26. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Boeing 737-800	50	9,1	-
2	Boeing 767-300	35	13,2	-
3	Boeing 777-200	23	17,4	-
4	Boeing 777-300	17	13,3	-
5	Boeing 787-8	25	5,1	4
6	Boeing 787-9	17	1,8	7
7	Airbus A350-900	-	-	18
8	Airbus A350-1000	-	-	13



	Boeing 737-800	Boeing 767-300	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9
Japan Airlines	50	35	23	17	25	17

Figure 128. Number of aircraft in the airline fleet



	Boeing 737-800	Boeing 767-300	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9
Japan Airlines	9.1	13.2	17.4	13.3	5.1	1.8

Figure 129. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 9 years. The youngest aircraft is about 2 years old (Boeing 787-9). The company made an order for 42 new aircraft [155]–[157].

AVI.4.7 ALL Nippon Airways airline

All Nippon Airways Co., Ltd., also known as Zennikkū or ANA, is the second-largest international airline in the country after Japan Airlines and the largest airline operating domestic flights. The airline operates flights to 49 airports in Japan and 22 foreign airports.

Table 27, Figure and Figure display information about the ALL Nippon Airways fleet, the number and the average age of the aircraft.

Table 27. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A320-200	8	22,6	-
2	Airbus A320neo	7	1,2	-
3	Airbus A321-200	4	2,2	-
4	Airbus A321neo	11	0,6	1
5	Boeing 737-700	7	12,4	-
6	Boeing 737-800	40	6,2	-
7	Boeing 767-300	43	16,6	-
8	Boeing 777-200	22	14	1
9	Boeing 777-300	29	12,5	1
10	Boeing 787-8	36	5,8	-
11	Boeing 787-9	30	2,5	-
12	Dash 8 Q400	24	9,96	-
13	Boeing 787-10	1	0,1	-
14	Airbus A380	-	-	3
15	Boeing 777F	-	-	2
16	Boeing 777X	-	-	20
17	Boeing 787-10	-	-	3
18	Mitsubishi MRJ-90	-	-	15

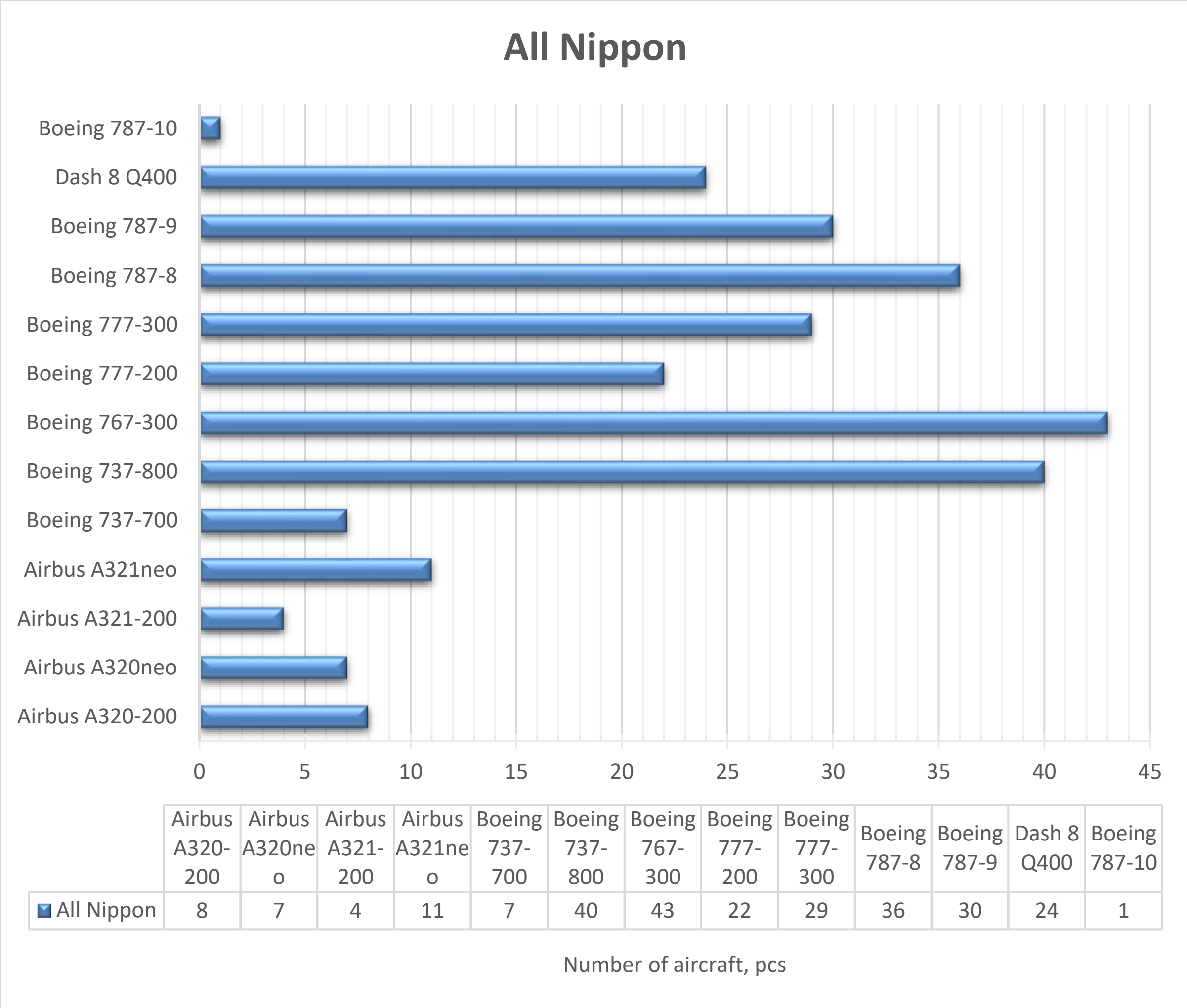
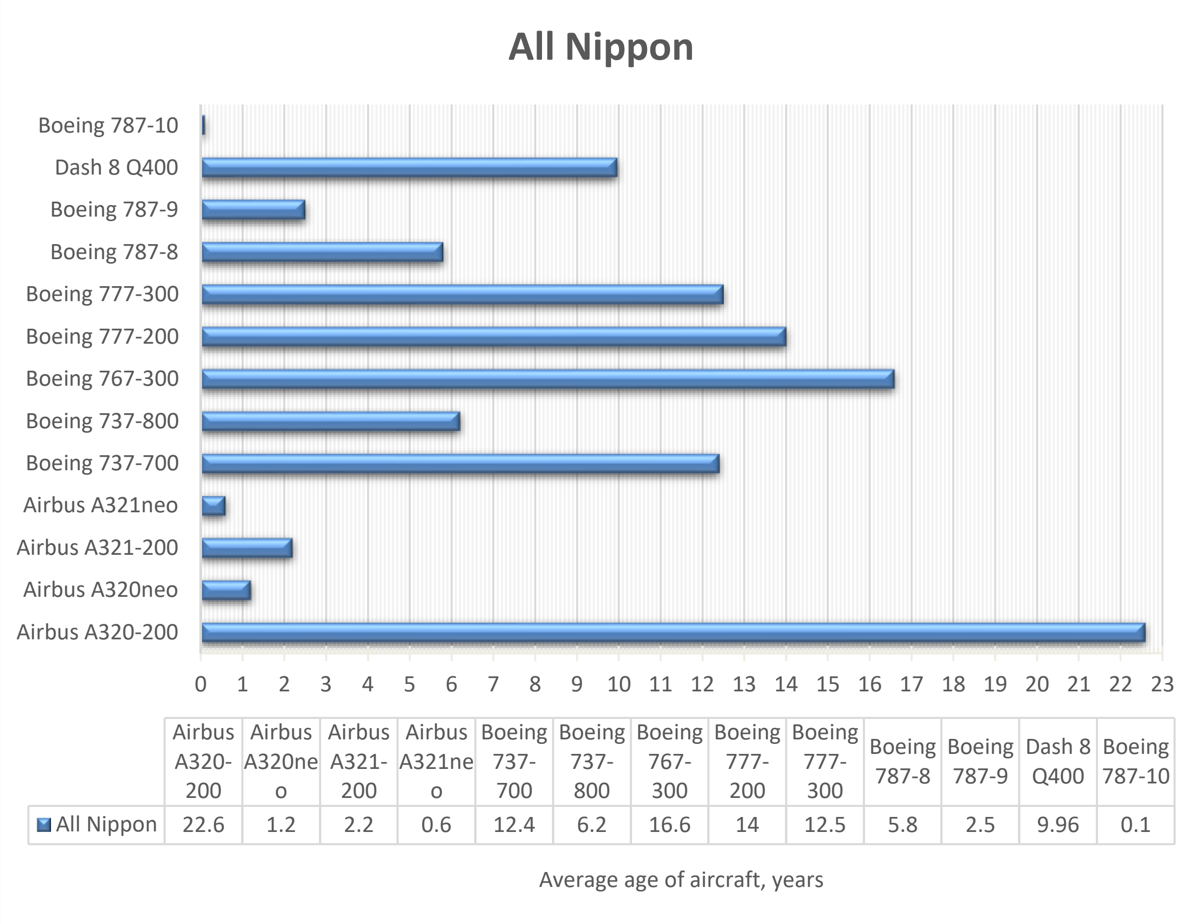


Figure 130. Number of aircraft in the airline fleet



	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A321neo	Boeing 737-700	Boeing 737-800	Boeing 767-300	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9	Dash 8 Q400	Boeing 787-10
All Nippon	22.6	1.2	2.2	0.6	12.4	6.2	16.6	14	12.5	5.8	2.5	9.96	0.1

Figure 131. The average age of aircraft type in teh airline fleet

The average age of ALL Nippon Airways fleet is about 12 years. The company has ordered 15 MRJ-90s of the Japanese company Mitsubishi, the deliveries of which will begin in 2020. Starting from 2019, the deliveries of the Airbus A380 are expected. Also in 2019, the deliveries of Boeing 777 are expected. The deliveries of 20 Boeing 777X aircraft will begin in 2020 [158]–[160].

AVI.4.8 Qantas airline

Qantas is Australia's largest airline operating domestic and international flights around the world. Table 28, Figure 132 and Figure 133 display information about the Qantas fleet, the number and the average age of the aircraft.**Error! Reference source not found.**

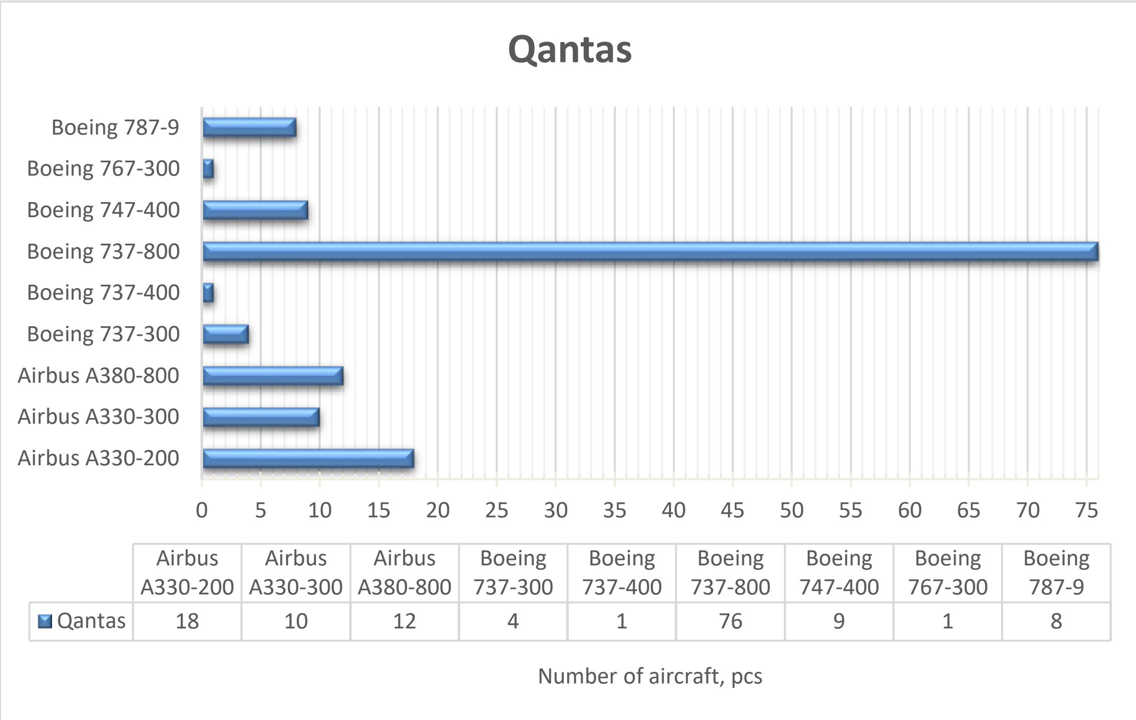
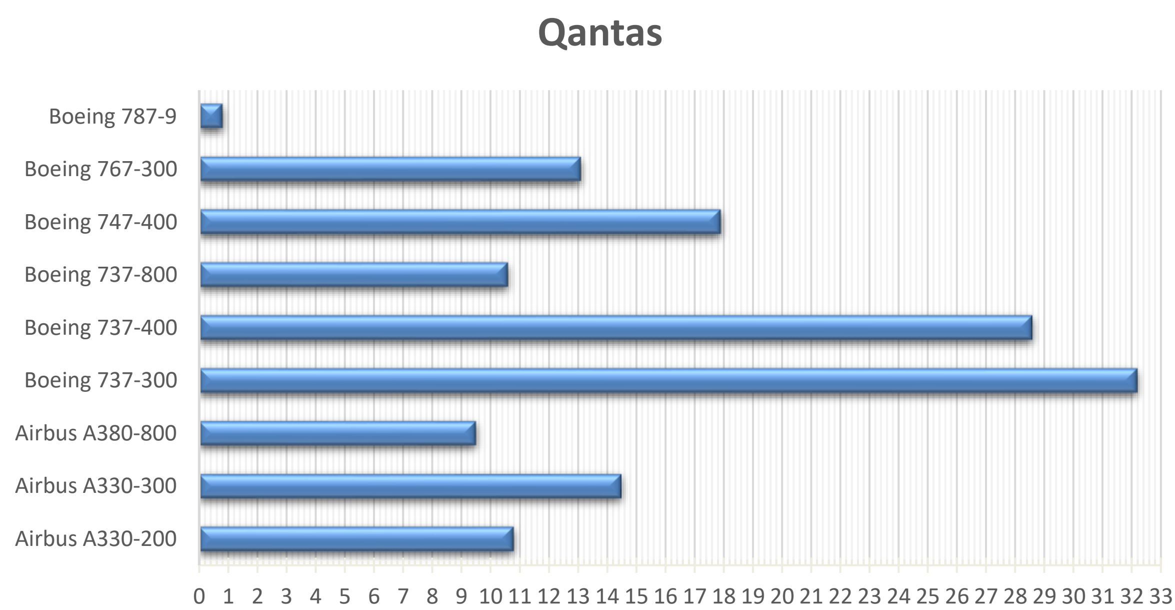


Table 28. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A330-200	18	10,8	-
2	Airbus A330-300	10	14,5	-
3	Airbus A380-800	12	9,5	8
4	Boeing 737-300	4	32,2	-
5	Boeing 737-400	1	28,6	-
6	Boeing 737-800	76	10,6	-
7	Boeing 747-400	9	17,9	-
8	Boeing 767-300	1	13,1	-
9	Boeing 787-9	8	0,8	9



	Airbus A330-200	Airbus A330-300	Airbus A380-800	Boeing 737-300	Boeing 737-400	Boeing 737-800	Boeing 747-400	Boeing 767-300	Boeing 787-9
Qantas	10.8	14.5	9.5	32.2	28.6	10.6	17.9	13.1	0.8

Average age of aircraft, years

Figure 133. The average age of aircraft type in the airline fleet

The average age of the Qantas fleet is about 14 years. The youngest aircraft is 0.8 years old (Boeing 787-9). Boeing 787-9s will replace 747-400s [161]–[164].

AVI.5 North America airlines

North America airlines are gradually acquiring aircraft of large seating capacity, not only because of economic efficiency but also because major airports are approaching the limits of their slots. Major regional 50-seat aircraft were replaced with 76-seat aircraft. Similarly, there was also some demand for narrow-body aircraft in the class of 170-229 seats, such as the A321 and B737-900ER. There is a demand in the class of 120-169 seats, such as the A319/A320 and B737-700/800, which are still the main ones. In addition, some companies are hoping to get the B787 aircraft, which can reach its capacity limit as a narrow-body aircraft.

Since there is fierce competition on domestic routes, major airlines in North America have struggled to expand their business on international routes. The demand for wide-body aircraft, such as the A350 and B777/787, has increased. Narrow-body aircraft will account for 56% of all deliveries, and the aircraft of an up to 100-seat capacity, including turboprop aircraft, will account for 23% [91].

AVI.5.1 American Airlines

American Airlines is one of the largest air carriers in the world. American Airlines operates regular flights within the United States, as well as to Canada, the Caribbean, Latin America, Russia and Asian countries. Table 29, Figure 134 and Figure 109 display information about the fleet of American Airlines, the number and the average age of the aircraft.

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Table 29.Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319	127	14,9	-
2	Airbus A320	48	17,9	-
3	Airbus A321	220	6,5	-
4	Airbus A330	24	11,5	-
5	Boeing 737-8	326	8,7	85
6	Boeing 757-223	34	19.3	-
7	Boeing 767-323(ER)	23	20.2	-
8	Boeing 777	67	14,3	-
9	Boeing 787	41	2,3	50
10	Bombardier CRJ-200ER	35	-	
11	Bombardier CRJ-701ER	141	-	-
12	Bombardier CRJ-900ER	118	-	-
13	Embraer ERJ-140LR	37	-	-
14	Embraer ERJ-145LR	120	-	-

15	Embraer ERJ-190AR	20	11,3	-
16	Embraer ERJ-175LR	159	-	-
17	McDonnell Douglas MD-82	29	-	-
18	McDonnell Douglas MD-83	29	20,5	-
19	Airbus A321neo	-	-	100

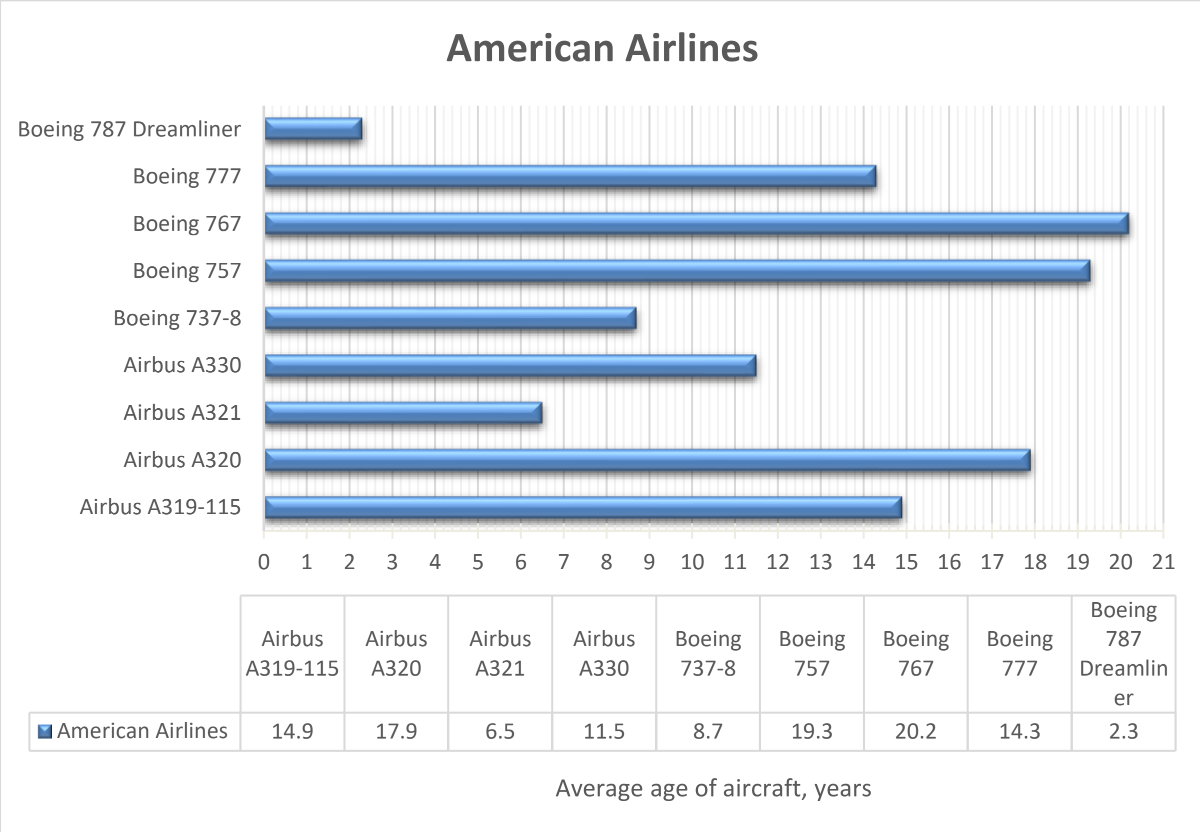


Figure 109. The average age of aircraft type in the airline fleet

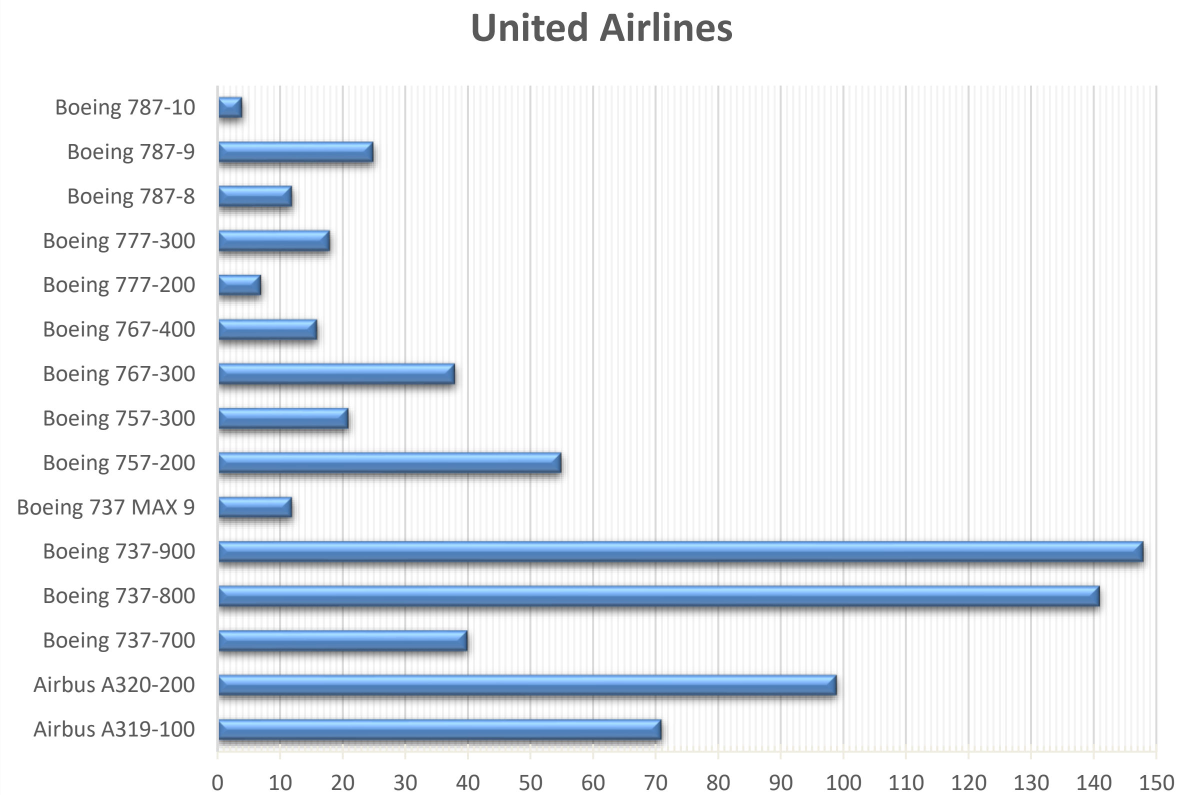
The average age of the airline fleet is about 13 years. The delivery of the Airbus A321neo is scheduled for 2019. Some airplanes will gradually begin to be decommissioned from 2021, with Boeing 787-9 coming to replace them. The oldest Boeing 737-800s in the amount of 45 aircraft will be decommissioned starting from 2020. The deliveries of 40 Boeing 737MAX8s are temporarily postponed to 2025. In 2019, the Boeing 767-300ER will be removed from the airline fleet. This model will be replaced by Boeing 787-8. From the beginning of 2020, 22 Boeing 787-8s will be delivered. Starting from 2023, 25 787-89s will be delivered to the company. All Embraer and McDonnell Douglas aircraft will be removed from the airline fleet by the end of 2019. In 2018, in addition to its original order for 42 aircraft, the airline ordered another 47 Boeing 787 aircraft [165]–[169].

AVI.5.2 United Airlines

United Airlines is an American airline, one of the largest in the United States and in the world. The route network of the company connects most of the countries of Asia, Africa, Australia, Western Europe, and also provides communication between cities in the US domestic market. In general, the company operates 235 domestic and 138 international destinations. Table 30, Figure 110 and Figure 111 display information about the United Airlines fleet, the number and the average age of the aircraft.

Table 30. Airline fleet, number and age of the aircraft

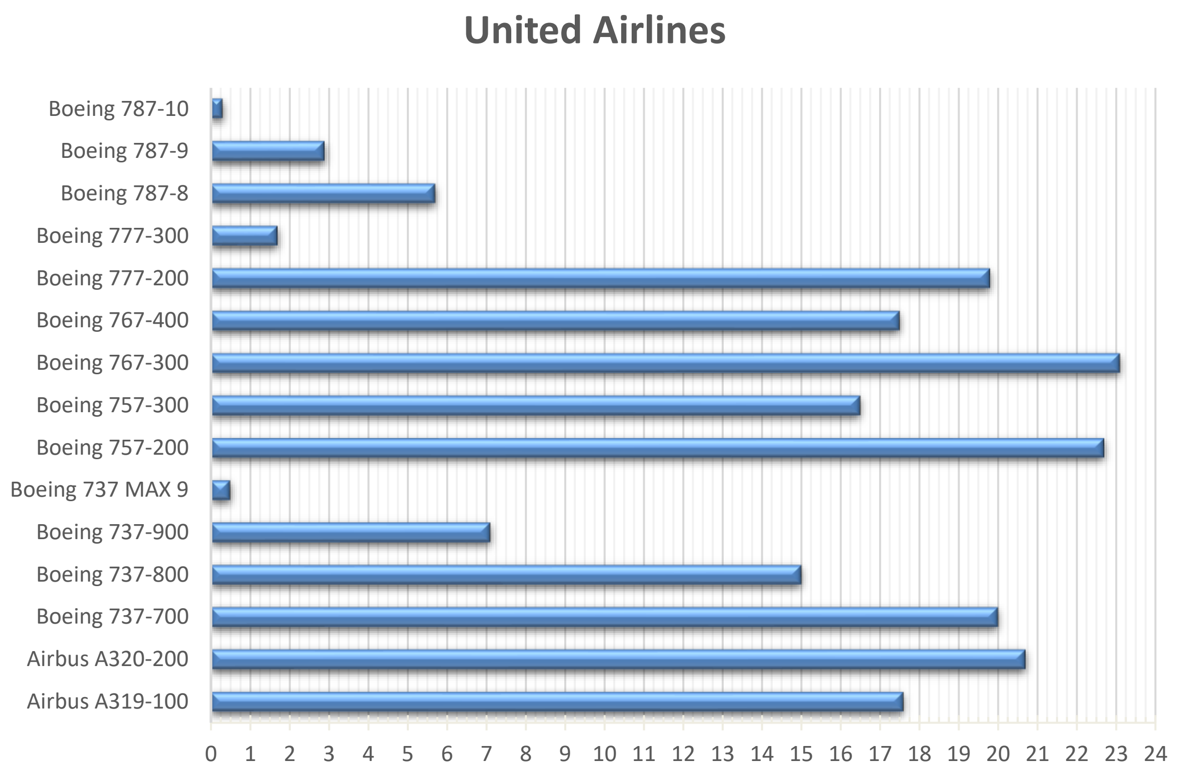
No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	71	17,6	30
2	Airbus A320-200	99	20,7	1
3	Boeing 737-700	40	20	-
4	Boeing 737-800	141	15	-
5	Boeing 737-900	148	7,1	-
6	Boeing 737 MAX 9	12	0,5	49
7	Boeing 757-200	55	22,7	-
8	Boeing 757-300	21	16,5	-
9	Boeing 767-300	38	23,1	-
10	Boeing 767-400	16	17,5	-
11	Boeing 777-200	7	19,8	-
12	Boeing 777-300	18	1,7	-
13	Boeing 787-8	12	5,7	-
14	Boeing 787-9	25	2,9	-
15	Boeing 787-10	4	0,3	10
16	Airbus A350	-	-	45
17	Boeing 737 MAX 10	-	-	100



	Airbus A319-100	Airbus A320-200	Boeing 737-700	Boeing 737-800	Boeing 737-900	Boeing 737 MAX 9	Boeing 757-200	Boeing 757-300	Boeing 767-300	Boeing 767-400	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9	Boeing 787-10
United Airlines	71	99	40	141	148	12	55	21	38	16	7	18	12	25	4

Number of aircraft, pcs

Figure 110. Number of aircraft in the airline fleet



	Airbus A319-100	Airbus A320-200	Boeing 737-700	Boeing 737-800	Boeing 737-900	Boeing 737 MAX 9	Boeing 757-200	Boeing 757-300	Boeing 767-300	Boeing 767-400	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9	Boeing 787-10
United Airlines	17.6	20.7	20	15	7.1	0.5	22.7	16.5	23.1	17.5	19.8	1.7	5.7	2.9	0.3

Average age of aircraft, years

Figure 111. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 12 years. As of 2019, the company has ordered more than 200 aircraft of various types [170]–[172].

AVI.5.3 Delta AirLines

Delta Airlines is an American airline, the largest in the world in all respects. The route network covers the countries of North America, South America, Europe, Asia, Africa, the Middle East and the Caribbean. Table 31, Figure 112 and Figure 113 display information about the Delta Airlines fleet, the number and the average age of the aircraft.

Table 31.Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A220-100	14	0,2	-

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
2	Airbus A319-100	57	17,1	-
3	Airbus A320-200	61	23,5	-
4	Airbus A321-200	72	1,3	-
5	Airbus A330-200	11	13,9	-
6	Airbus A330-300	31	10,1	-
7	Airbus A350-900	13	1,1	-
8	Boeing 717-200	91	17,4	-
9	Boeing 737-700	10	10,1	-
10	Boeing 737-800	77	17,5	-
11	Boeing 737-900	120	2,7	-
12	Boeing 757-200	111	22,3	-
13	Boeing 757-300	16	16,1	-
14	Boeing 767-300	58	22,9	-
15	Boeing 767-400	21	18,2	-
16	Boeing 777-200	18	14,1	-
17	MD-88	86	28,2	-
18	MD-90	46	21,9	-
19	CRJ-100ER	3	18,7	-
20	CRJ-200LR	124	15,5	-
21	CRJ-701ER	51	14,1	-
22	CRJ-900LR	159	8,7	-
23	ERJ-170	21	12,3	-

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
24	ERJ-175	101	5,7	-
25	Airbus A330-900	-	-	2

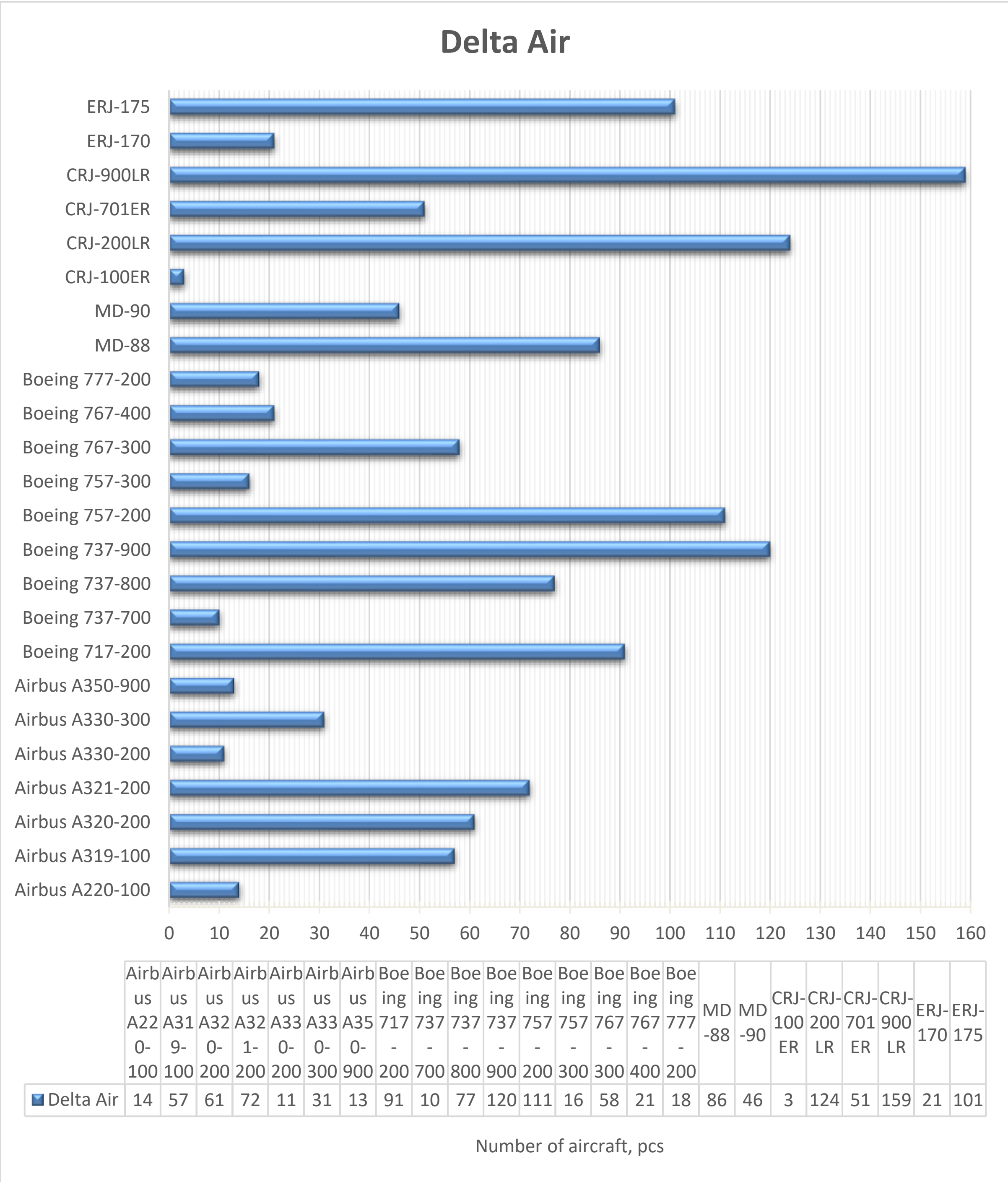
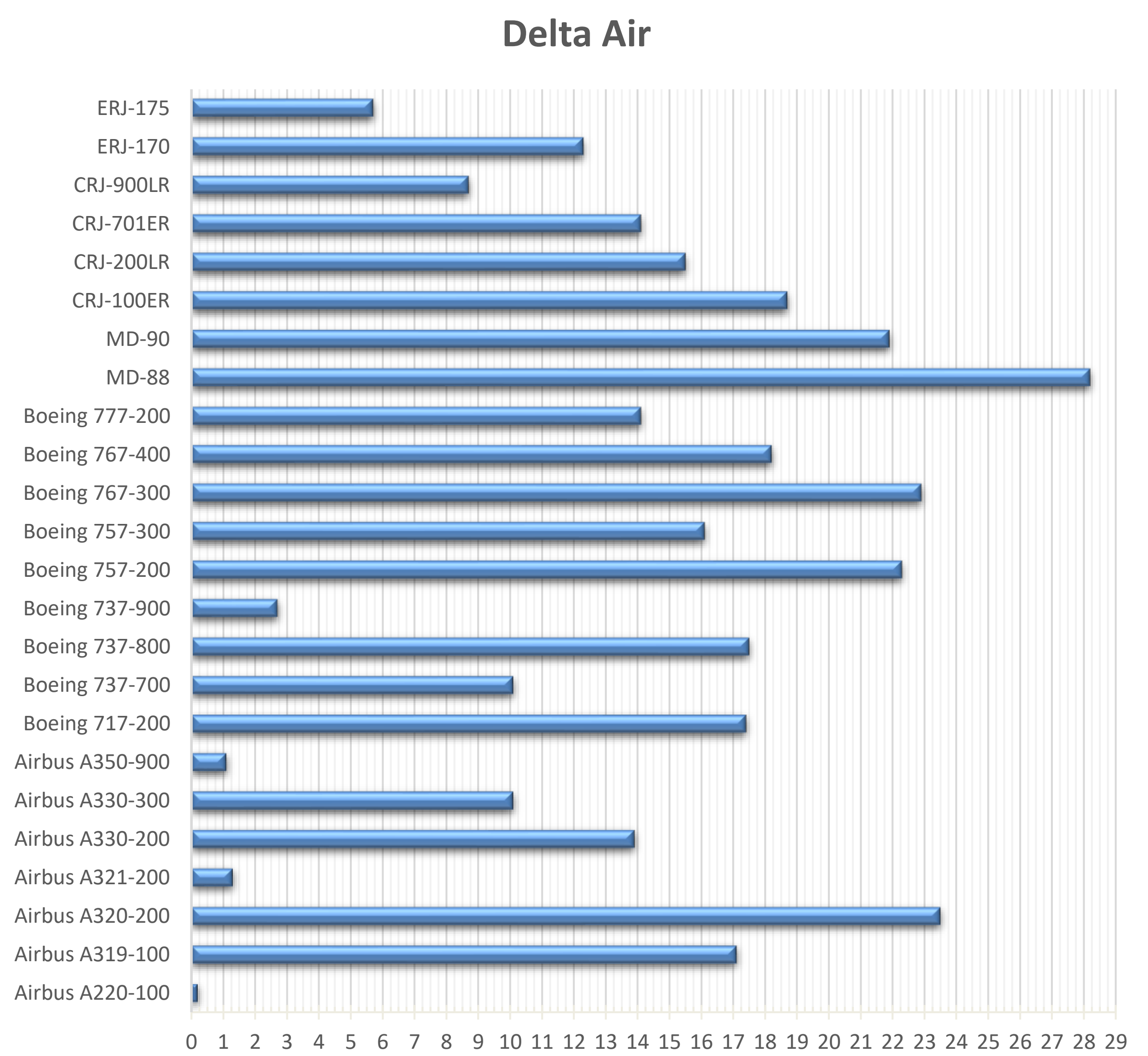


Figure 112. Number of aircraft in the airline fleet



	Airbus A220-100	Airbus A319-100	Airbus A320-200	Airbus A321-200	Airbus A330-200	Airbus A330-300	Airbus A350-900	Boeing 717-200	Boeing 737-700	Boeing 737-800	Boeing 737-900	Boeing 757-200	Boeing 757-300	Boeing 767-300	Boeing 767-400	Boeing 777-200	MD-88	MD-90	CRJ-100ER	CRJ-200LR	CRJ-701ER	CRJ-900LR	ERJ-170	ERJ-175
Delta Air	0.2	17	24	1.3	14	10	1.1	17	10	18	2.7	22	16	23	18	14	28	22	19	16	14	8.7	12	5.7

Average age of aircraft, years

Figure 113. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 14 years. The airline fleet consists of 1372 aircraft of various types. The delivery of 2 Airbus A330-900s is expected [173]–[175].

AVI.5.4 Air Canada airline

Air Canada is the largest airline in Canada and the national carrier of the country. The airline operates 21 domestic and 81 international flights to cities in North America, South America, Europe, Asia and Oceania. Including regional partners, Air Canada flies to more than 180 destinations in 46 countries and on five continents. Table 32, Figure 114 and Figure 115 display information about the Air Canada fleet, the number and average age of the aircraft.

Table 32. Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319	16	21,6	-
2	Airbus A320	42	25,5	45
3	Airbus A321	18	15,9	-
4	Airbus A330	8	18,5	4
5	Boeing 737	22	0,8	43
6	Boeing 767-375(ER)	8	29.5	-
7	Boeing 777	25	9,3	-
8	Boeing 787	35	2,8	2
9	Embraer ERJ-190	19	11,5	-

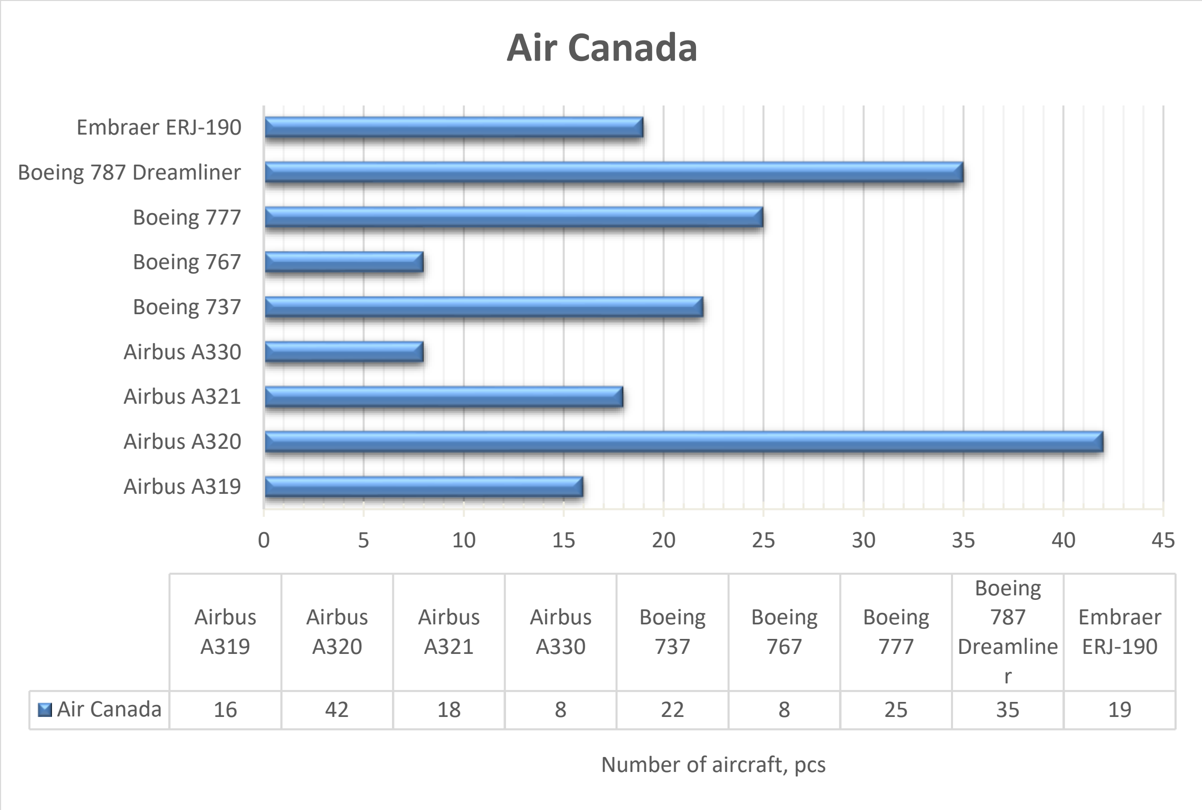


Figure 114. Number of aircraft in the airline fleet

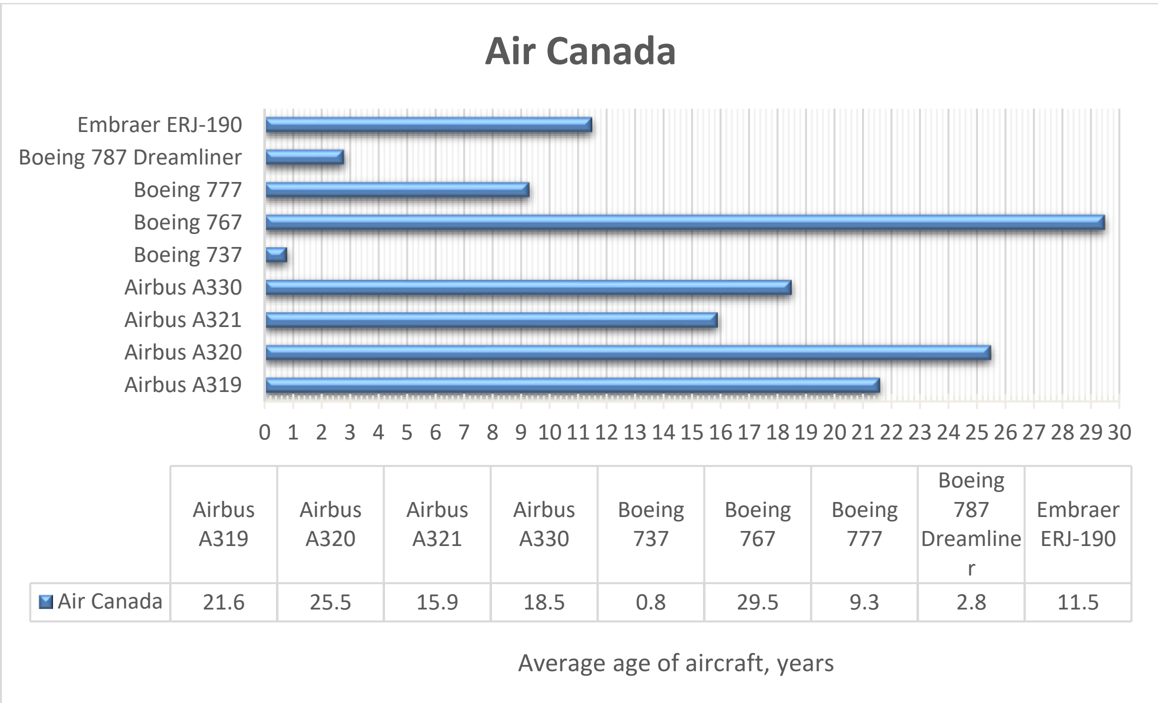


Figure 115. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 13 years. The Air Canada fleet is constantly updated, so for the next 5 years, an upgrade of almost 100 aircraft is planned. Airbus A319-

100, Airbus A320-200, Airbus A321-200 are scheduled to be decommissioned throughout 2017-2021. These types of aircraft will be replaced with Boeing 737MAX8/9. Boeing 737-9 is planned to replace Airbus A320. The Boeing 767-375 (ER) fleet has an average age of 29.5 years. Therefore, this type of aircraft is replaced with Boeing 787-8 and 767-300ER, the deliveries of these types of aircraft have begun in 2015 and are scheduled to be completed in 2019. From the end of 2019, the delivery of Airbus A220-300 is planned to be started and will last until 2022 [176]–[179].

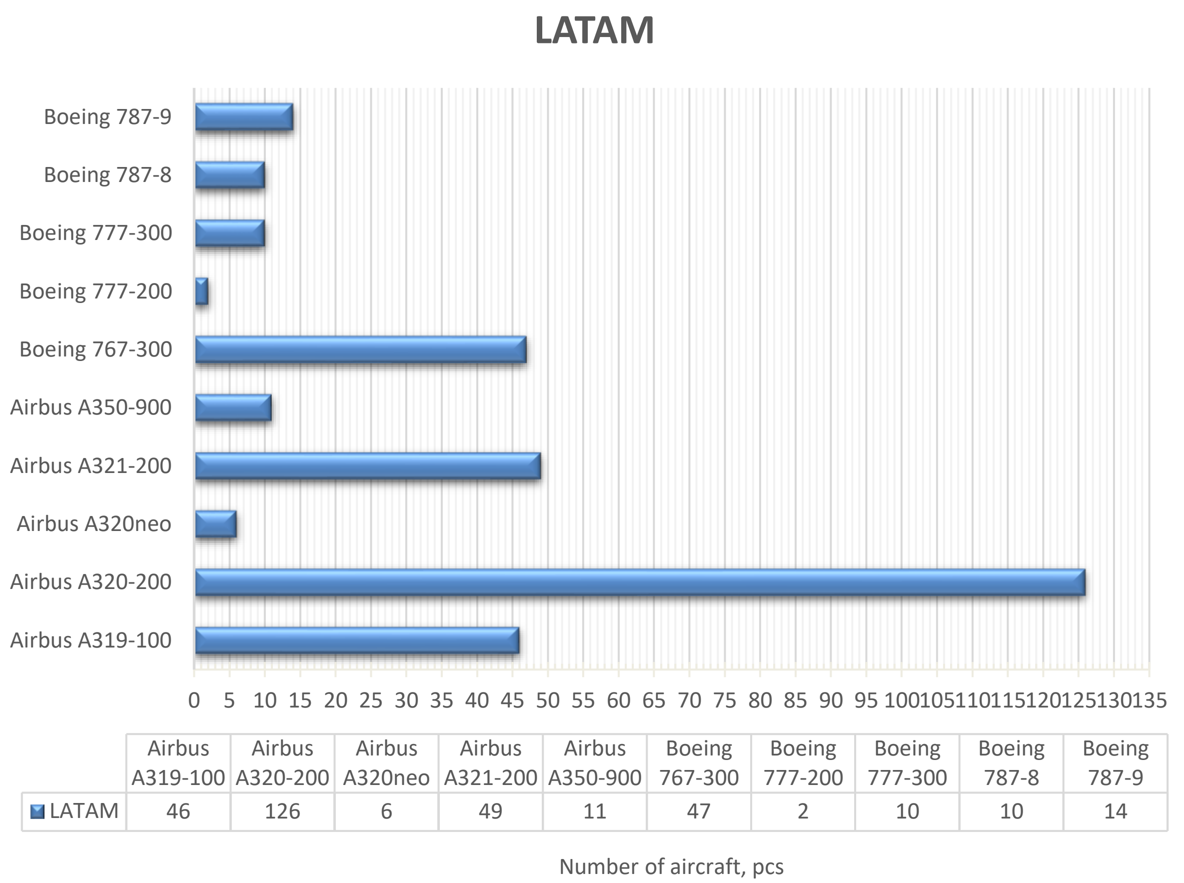
AVI.6 Latin America airlines

AVI.6.1 LATAM Airlines

LATAM Airlines is a South American aviation holding. The airline provides regular passenger transportation to Brazilian airports, international flights to Europe, as well as to North and South America. Table 33, Figure 116 and Figure 117 display information about the of LATAM Airlines fleet, the number and the average age of the aircraft.

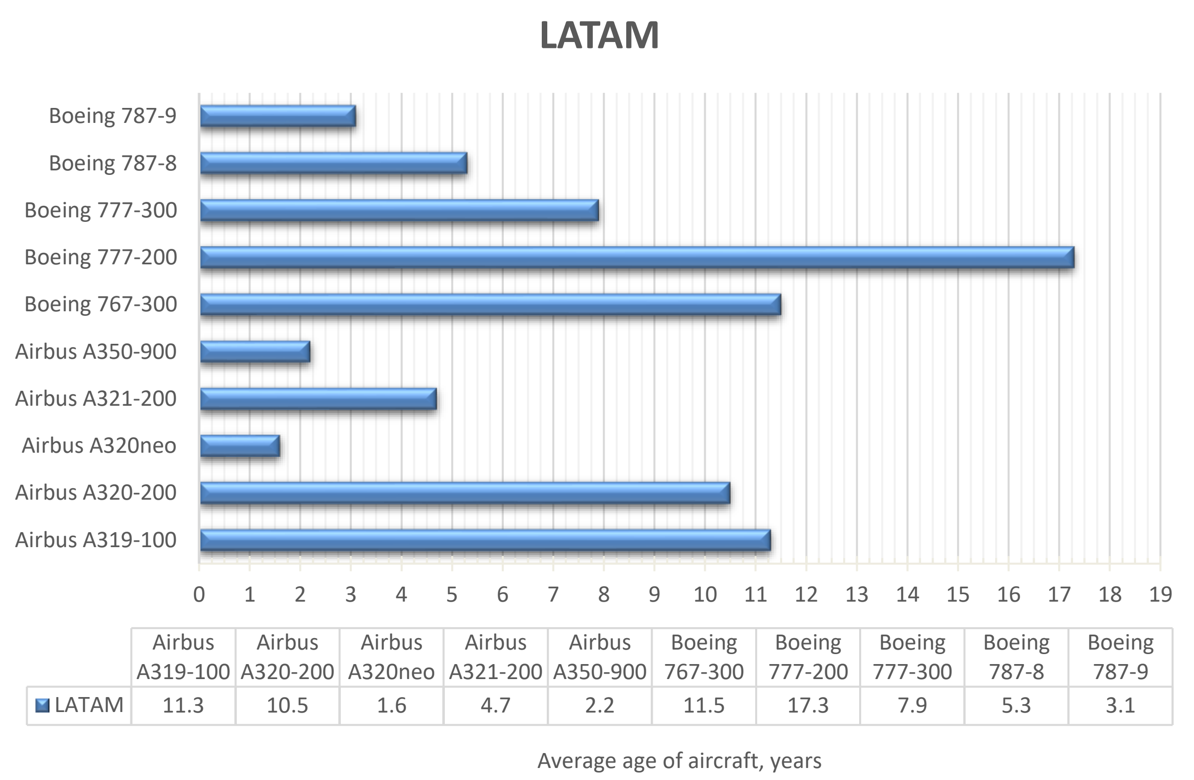
Table 33.Airline fleet, number and age of the aircraft

No.	Aircraft type	Number of aircraft, pcs	Average age of aircraft type, years	New orders, pcs
1	Airbus A319-100	46	11,3	-
2	Airbus A320-200	126	10,5	-
3	Airbus A320neo	6	1,6	4
4	Airbus A321-200	49	4,7	2
5	Airbus A350-900	11	2,2	-
6	Boeing 767-300	47	11,5	-
7	Boeing 777-200	2	17,3	-
8	Boeing 777-300	10	7,9	-
9	Boeing 787-8	10	5,3	-
10	Boeing 787-9	14	3,1	-
11	Airbus A350-1000	-	-	12
12	Airbus A321neo	-	-	1



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A350-900	Boeing 767-300	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9
LATAM	46	126	6	49	11	47	2	10	10	14

Figure 116. Number of aircraft in the airline fleet



	Airbus A319-100	Airbus A320-200	Airbus A320neo	Airbus A321-200	Airbus A350-900	Boeing 767-300	Boeing 777-200	Boeing 777-300	Boeing 787-8	Boeing 787-9
LATAM	11.3	10.5	1.6	4.7	2.2	11.5	17.3	7.9	5.3	3.1

Figure 117. The average age of aircraft type in the airline fleet

The average age of the airline fleet is about 8 years. The backlog of orders for new aircraft includes 19 different types of aircraft[180].

AVI.7 Conclusions

Based on the analysis, it can be concluded that almost all airlines having B757 and B767 aircraft in their fleet need to replace the fleet within 3 years, including UIA and Azur Air.

Boeing executives have talked for several years about the NMA, saying they see an opportunity for an aircraft to replace stalwart 767s and 757s. In terms of range and capacity, those aircraft sit between the 737 Max 10 and 787-8, making them uniquely suited for certain long-haul, medium-demand routes, including many across the Atlantic. Boeing has said its NMA would seat 200-270 passengers and have a range of up to 5,000nm (9,260km).

The total sales opportunity remains unclear, but Boeing has produced about 2,170 757s and 767s to date, of which nearly 1,470 remain in service, according to Flight Fleets Analyzer. US carriers American Airlines, Delta Air Lines and United Airlines alone operate nearly 400 of the types [181].

The A321neo has already outsold the 757's total sales by more than half. Flight Fleets Analyzer shows that at the end of January Airbus had a backlog for 1,897 A321neos, including 97 LRs.

The emergence of a larger B737Max has redressed the situation. The B737carries the same number of passengers as the A321, but has a better, more efficient wing and it is 5,000lb lighter than the competition. The launch of a new aircraft began in mid-2017, but the market reaction is still weak. Boeing has accumulated 403 Max 10 firm orders since launch, Flight Fleets Analyzer shows. Boeing concedes that some of these came through conversions by customers of orders for the Max 9. Flight Fleets Analyzer also shows another 425 orders where the variant could be either the B737Max8 or B737Max9. Boeing also has more than 870 Max orders where no variant has been declared. While the Max 10 created a weapon in the Boeing armoury to counter the A321neo family, it is generally viewed as an interim step until the NMA comes along in about six years' time.

When 757 production ended in 2005, Boeing had delivered 1,049 aircraft. That is why it can be concluded that the NMA market being at least four times that level, putting NMA demand at more than 4,000 units. Flight Ascend Consultancy's long-term market forecast indicates that building a viable business case for NMA could be challenging. However, a demand scenario can be painted which could deliver sales that exceed a couple of thousand aircraft over the production life.

GE Aviation, whose CFM International partnership is seen as a front-runner to power the NMA, expects a launch decision will be needed in 2019 if the target service-entry of the mid-2020s is to be achieved. Airbus for its part does not see a vacant market in the sector that the NMA is aimed at. The investment in the development of the A320 family as well as the global A320 production and assembly centres has probably been recovered by Airbus a long time ago. So unless the NMA offers hugely lower operational cost – i.e., through fuel burn and maintenance costs – Airbus will always be able to offer their A321neo/A321LR or the A330neo at a significantly lower cost.

Single- and twin-aisles are known to have different operating economics and different manufacturing costs. Most likely, a Boeing NMA would sell to people who can use this jet to its full capability, about 240-270 seats, and 4,000-5,000nm[89].

According to aircraft market analysis, it can be concluded that half of the current fleet will be less than 15 years of age by 2026. Aircraft that will be more than 30 years of age will almost certainly have been retired by that point. That leaves around 900 aircraft aged 15-25 years that include 420 A321s, 270 A330-200s, 90 757s and 130 767s. Thus, the NMA cannot really be said to be a 757/767 replacement, as is too late. From Boeing's perspective, it may well be attractive to capture current Airbus A321neo.

The largest current operators of these mid-market types are the three US majors American, Delta and United, followed by the three largest Chinese airlines (China Southern, China Eastern, Air China). These six airlines fly over 1,000 aircraft in the size bracket, almost one-third of the total fleet. They also represent about a third of the aircraft in the 15-25-year age bracket.

However, American has committed to order more 787-8s to replace its remaining 767 fleet and will likely have replaced all 757s by the mid-2020s. Delta thus appears to be a key potential customer, as does United. Neither has ordered a direct replacement for its 767 fleet yet, and Delta still needs to place more orders to supplant its younger 757s.

The Chinese majors will also be potential operators, primarily for A321/A330-200 [88].

By 2026, Turkish Airlines, Vietnam Airlines, Air Canada, Japan Airlines, Air France and Air India will be replacing airplanes aged 15–25 years old. Leasing companies will lease a new aircraft based on their experience of using 767-300ER, B787, A330-200 and A321.

Annex VII Demand forecast calculations methodology

This annex provides an insight over the methodology used for calculating the forecasted aircraft demand. The approach used in this method is based on the air traffic demand forecast, so that the necessary fleet to satisfy this demand is estimated based on the following airline performance parameters:

- Load factor (LF): The fraction of seats occupied on the aircraft per flight as a percentage of the total.
- Utilization time (UT): Hours per day in which the aircraft is on service (also called block hours).
- Block's mean speed (V): Mean speed of flight per block hour.
- Average of seats offered per aircraft (s).

Using the traffic volume forecast values of Revenue Passenger Miles (RPM) and taking the estimated annual traffic growth TG_k, it is possible to calculate the traffic volume for the next year. Thus, for each year, say k, it yields:

$$RPM_k = (TG_k + 1) \cdot RPM_{k-1}.$$

To transform the passenger volumes to required capacity, (ASM –Available Seats per Mile), the estimated load factor for every year is required, so that:

$$ASM_k = \frac{RPM_k}{LF_k},$$

and the required daily capacity is

$$ASM_{k,day} = \frac{ASM_k}{365}.$$

Once the capacity has been estimated, the number of aircraft (n) composing the fleet of the year k can be calculated as:

$$n_k = \frac{ASM_{k,day}}{V_k \cdot UT_k \cdot s_k}.$$

Note that the block's mean speed, utilization time and the number of seats are parameters that are assumed to change over time. The Airline Monitor [182] estimates the evolution of these parameters based on historical values available in its database.

Annex VIII Game analysis results of the reference scenario

This is the analysis of the reference scenario in which both Boeing and Airbus participate.

The following figure will show the payoff of each of the strategies arranged in this game:

Table 34. Nash equilibrium of reference scenario

Boeing\Airbus	*Maintain*	*Re-eng. A321XLR*
Maintain	B: 62.257– A: 74.810	B:44.326—A: 93.405
Launch NMA	B: 56.192 – A: 46.488	B: 49.724 – A: 54.248

As can be seen, the Nash equilibrium is indicated in yellow colour and it is a combination of two strategies, which are: Launch NMA that is B797 and re-engine of A321XLR.

This scenario is going to be analysed with two different software tools, GTE software and Gambit software. This is very useful to have a good understanding of how the different games work, their visualisation and how they can be resolved.

AVIII.1 Strategic game (GTE software)

As can be seen in the next figure, in the strategic form, one has to introduce the different inputs to the software like payoffs, players, a number of strategies and the strategies

The strategic game results are shown in the following table below:

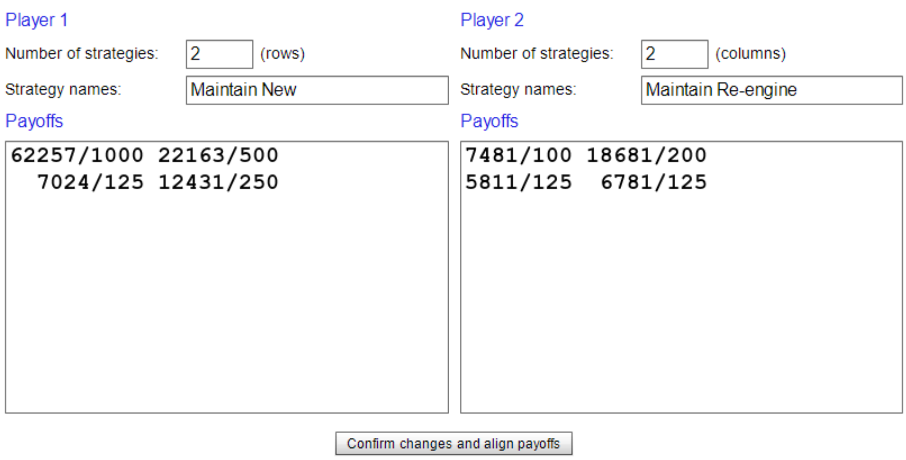


Figure 118. Strategic game

Table 35. The strategic game table of payoff

BOEING \ AIRBUS	Maintain	Re-engine
Maintain	7481/100 62257/1000	18681/200 22163/500
New	5811/125 7024/125	6781/125 12431/250

AVIII.2 Extensive Game (GTE software)

In this image, it can be seen the extensive game using the tree diagram form, in which Boeing and Airbus do not share the information which can be seen with the barrier between Boeing and Airbus strategies. Both players take their decisions simultaneously because this is a static game.

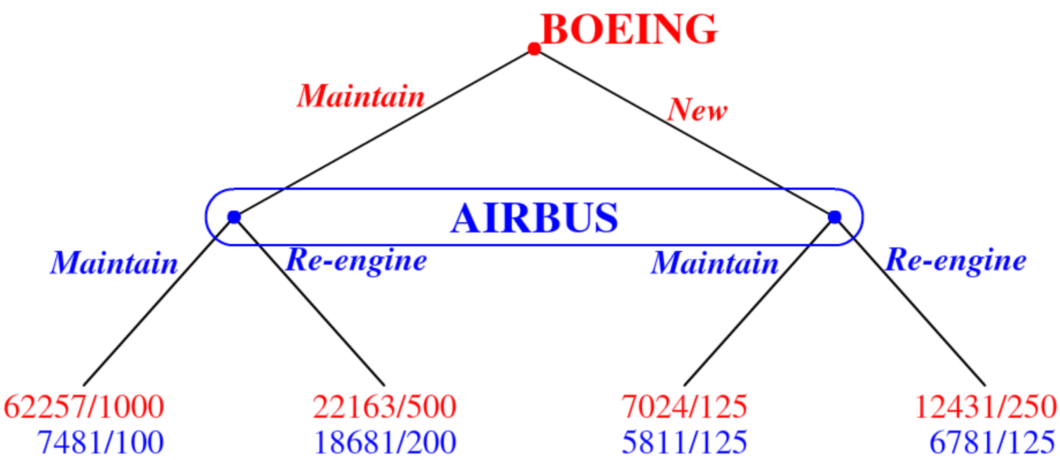


Figure 119. Extensive game

Results (GTE software)

Once games have been created, it is necessary to compute all Nash equilibriums, afterwards, the software will give the following output, which must be interpreted:

At the beginning of the output code, one can see two different matrices. The first one is Boeing's payoffs bimatrix and the second one is the Airbus' payoffs bimatrix.

Results are shown on the rational and decimal form. It is going to be provided with a deep explanation to get a better understanding of it.

It is shown that in this case it has been computed all Nash equilibriums possible and it is obtained only one equilibrium called "Extreme Equilibrium" (EE1).

For the player 1 (P1=Boeing), It is obtained that for its pair of strategies called (1) visualised as a vector 0 1, i.e., (Maintain, New) = (0,1), which means that the best strategy followed by Boeing is to invest its capital in the development of a new aircraft with an expected payoff of 48.377 mills. US$.

For the player 2 (P2=Airbus), It is obtained that for its pair of strategies called (1) visualised as a vector 0 1, i.e., (Maintain, Re-engine) = (0,1), which means that the best strategy followed by Boeing is to invest its capital in making re-engine with an expected payoff of 54.502 mill. US$.

In the section "Connected Component" it can be seen the strategy combination to reach the Nash equilibrium. In this case, the Nash equilibrium is reached with the combination of strategies "New" for Boeing and "Re-engine" for Airbus

```
SUCCESS

Strategic form:

2 x 2 Payoff player 1

           Maintain Re-engine
Maintain 62257/1000 22163/500
     New   7024/125 12431/250

2 x 2 Payoff player 2

         Maintain Re-engine
Maintain 7481/100 18681/200
     New 5811/125  6781/125


EE = Extreme Equilibrium, EP = Expected Payoffs

Rational:

EE 1 P1: (1) 0 1 EP= 12431/250 P2: (1) 0 1 EP= 6781/125

Decimal:

EE 1 P1: (1) 0 1.0 EP= 49.724 P2: (1) 0 1.0 EP= 54.248

Connected component 1:
{1}  x  {1}
```

Figure 120. GTE result

Now, it shows the software output code in which we can observe how it would work if we had completed the game only for one Nash equilibrium. As can be seen, the result is the same as the commented before.

```
SUCCESS

NormalForm 2 2
A           Maintain Re-engine
Maintain 62257/1000 22163/500
New         7024/125 12431/250

B           Maintain Re-engine
Maintain    7481/100 18681/200
New         5811/125  6781/125

Priors
Maintain  1/2 0.500
New       1/2 0.500

Maintain  1/2 0.500
Re-engine 1/2 0.500

Equilibrium
New                 1

Re-engine           1

£A          12431/250 49.724
£B           6781/125 54.248
```

Figure 121. Game result (only one equilibrium computed)

AVIII.3 Strategic game (Gambit software)

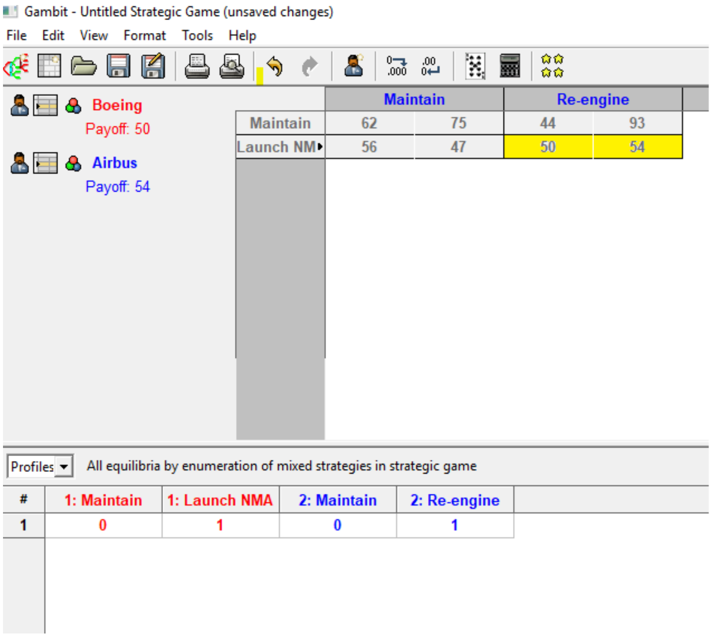


Figure 122. Gambit result (only one equilibrium computed)

As it can be seen in the 2x2 matrix each player has a row or column, and each Payoff is related to the situation in which the manufacturer of the rows plays with the strategies to which that row belongs, and the manufacturer to which the columns belong, exactly the same, but with the columns. Therefore, Boeing is willing to play the game in such a way that his strategies are associated with the ranks and strategies of Airbus, with the columns.

By computing Nash's balance by strategically analysing the game, the program establishes that the break-even point (the results highlighted in the matrix) between the different strategies is found when Boeing decides to put its products aside online and invest and bet on a new aircraft with its improvements in performance and reduced fuel consumption. Meanwhile, Airbus will decide to bet on a re-engineering of the A321XLR trying to stabilize and gain market share.

Additionally, the Nash equilibrium can be found by eliminating dominated strategies. Gambit software tool develops a process in which it eliminates the dominated strategies of the corresponding manufacturer, making it easier to clearly see the most optimal strategies.

Here in the game, it is appreciated that the elimination of the strategies dominated by others is eliminated by means of an X, a way of reflecting that the domain that is computing the software is strict, that is to say, that the strategy of the manufacturer is always worse than another one. In the case of a weak domain, it would be represented by a discontinuous and thin line.

Step1: Identification of dominated strategies

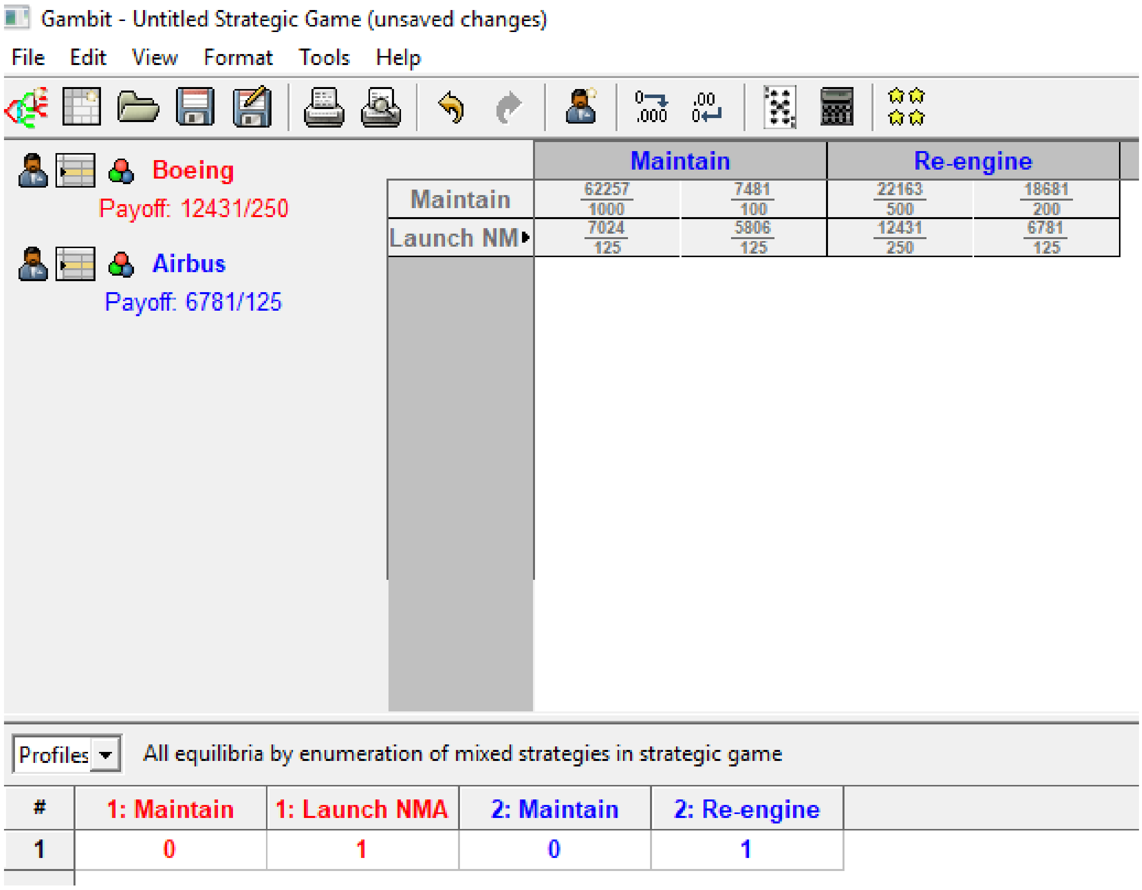


Figure 123. Identification of dominated strategies

Step2: Eliminate dominated strategies

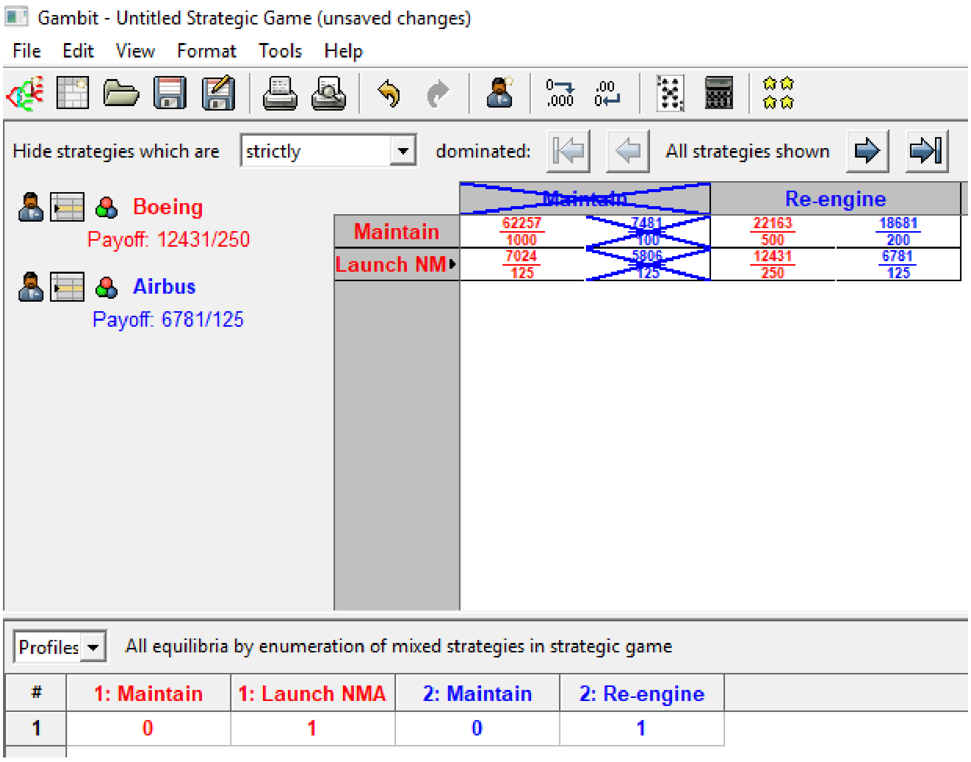


Figure 124. Elimination of dominated strategies level 1

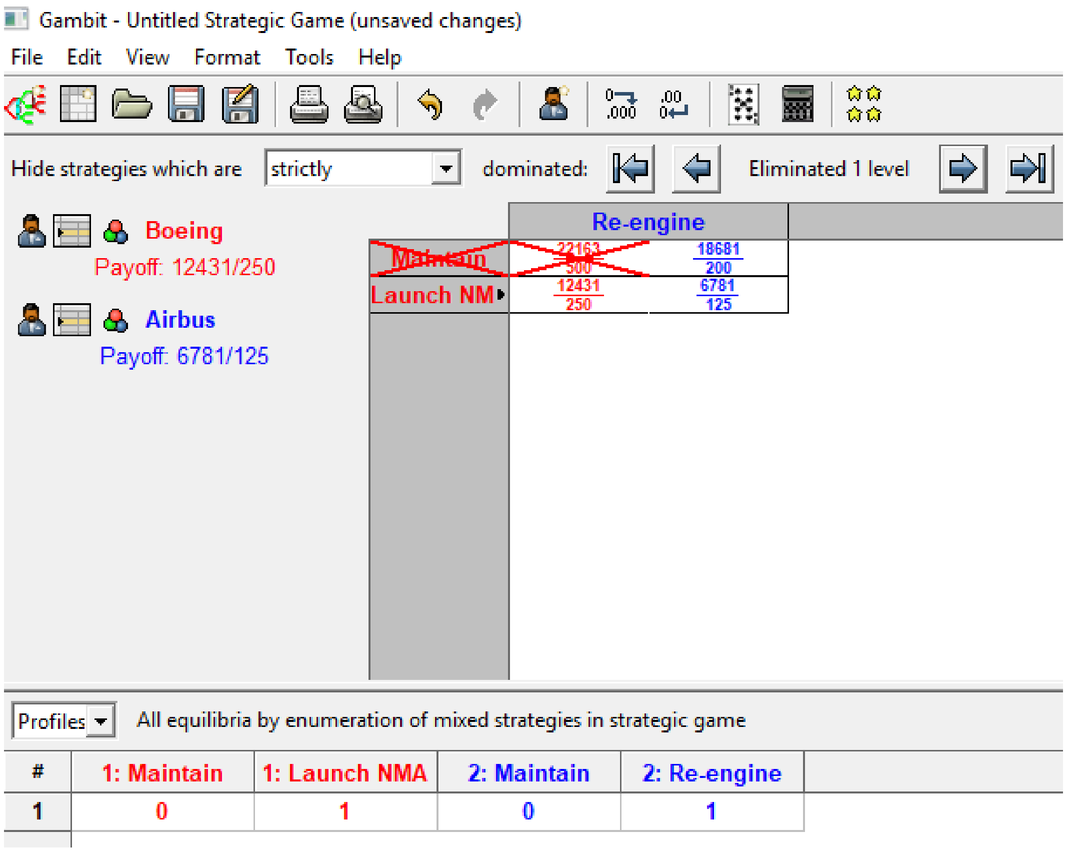


Figure 125. Elimination of dominated strategies level 2

Step 3: Find the Nash equilibrium

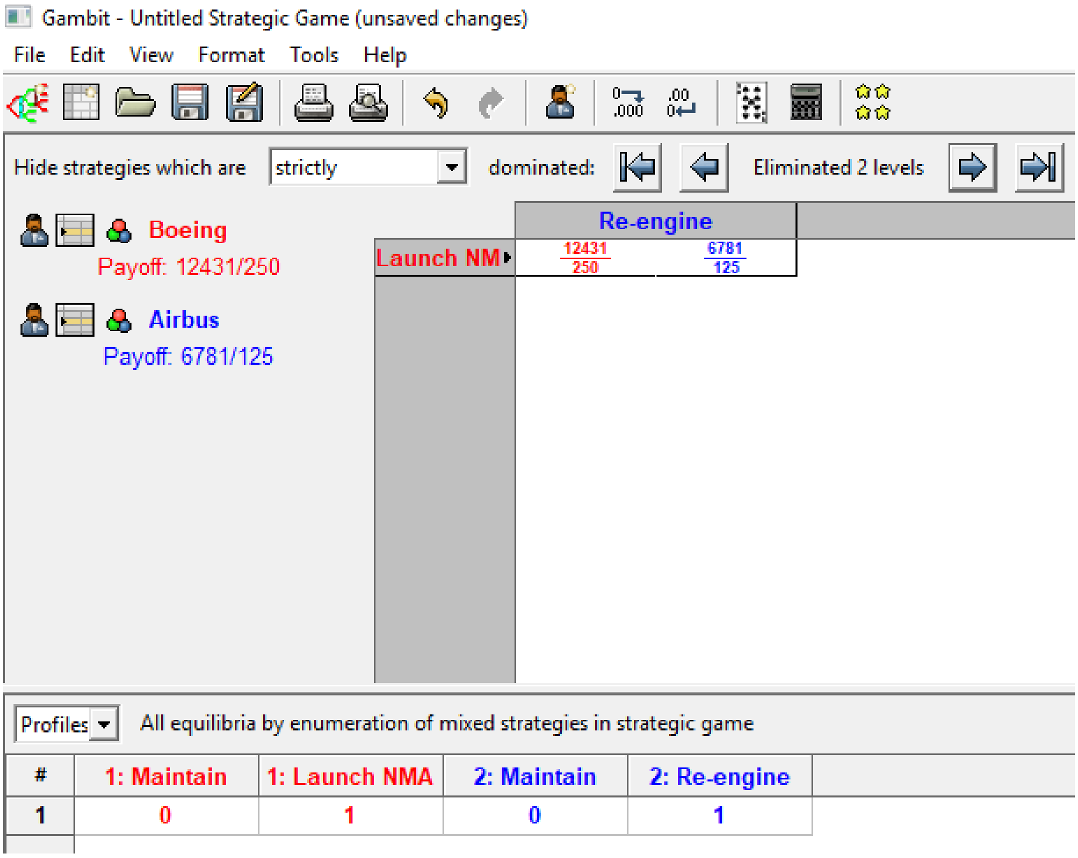


Figure 126. Find Nash equilibrium

EAs, it can be seen, the software develops the strategy process through levels, that is, it eliminates the strategies dominated by levels until it reaches the optimum point. With the rest of the scenarios, it is the same process as commented in this annex.

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