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Evolvability and Design Reuse in Civil Jet Transport Aircraft

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Abstract

A comprehensive investigation of evolvability and design reuse in new and historical civil jet transport aircraft was undertaken. The main purpose was to characterise the techniques and strategies used by aircraft manufacturers to evolve their designs. Such knowledge is essential to devise improved design methods for promoting the evolvability of new aircraft. To perform the study, jet aircraft from three large western manufacturers (Boeing, Airbus, and McDonnell Douglas) were investigated in depth. The academic and industrial literature was combed to find descriptions of design reuse and change across each major model of all three manufacturers. The causes and effects of the changes are explored, and the amenability of the different airframes to change are discussed. The evolution of the payload and range capabilities of the different aircraft was also investigated. From these studies, it was found that the initial approach to derivative designs appears somewhat ad hoc and that substantial modifications were devised in quick succession to increase both range and capacity. From the 1970s, two distinguishable patterns started to appear – a 'leap and branch' and a 'Z' pattern. The leaps correspond to major changes in both propulsion and airframe, whereas the branches are simple 'stretches' or 'shrinks'. The Z pattern, also documented by other authors, is a progressive increase in range, followed by a simple stretch, and then another increase in range. Design changes were investigated further by grouping them according to the assumed payload-range objectives set for the derivatives. Finally, the maximum changes found for salient geometrical design parameters amongst all the aircraft surveyed were documented. Developing methods to support the creation of leaps (especially across configurations) appears to be one of the most promising avenues for future research.

Keywords: Aircraft evolvability, derivative aircraft, commonality, design reuse, Boeing, Airbus, McDonnell Douglas.

1 Introduction

The development of a brand-new aircraft is often an expensive and risky undertaking. In fact, when decision-makers at the large aeroplane manufacturers elect to pursue a 'clean-sheet' design, they are often considered to be 'betting the company'. Although sometimes necessary to remain competitive, this type of clean-sheet development programme is rare, precisely because of the risks involved. Manufacturers are far more likely to devise only incremental advancements to existing designs. For such a strategy to be successful, however, the original ('baseline') design must be 'evolvable'. The evolvability (of an engineering system) is the extent to which the design of the system can be "inherited and changed across generations (over time)" [1].

An evolvable baseline design may help the manufacturer to reduce development and certification cost and time for descendants of this design. This is because it affords them the opportunity to reuse many design elements (such as segments of the airframe, components, systems, as well as development, manufacturing, and assembly processes), while upgrading only those that are necessary for subsequent generations to be competitive.

Several methods to design for and explore the evolvability of engineering systems have been devised. For an overview of these, the reader is directed to Cardin [2] which covers methods that promote 'flexibility', many of which are directly applicable to evolvability. A number of aircraft family-specific

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design strategies have also been proposed (see for example Willcox and Wakayama [3]). However, there seems to be a paucity in the literature of collated practical information related to the evolution of passenger transport aircraft. Such information was required by the authors to conduct related research involving the development of computational techniques to support designing aircraft to be more evolvable (see van Heerden [4]). In essence, to perform that work, it was required to obtain a detailed understanding of the design changes used in practice to evolve the designs of airliners.

Therefore, an investigation was conducted into evolvability practices in actual commercial transport aeroplanes. The purpose was to obtain i) qualitative descriptions of how components, design features, and airframe segments were reused or changed across generations of airliner designs; ii) to determine whether there are any distinguishable patterns in payload-range capability evolution, along with associated airframe changes; and iii) to determine the maximum changes in airframe geometrical design parameters achieved across baseline and derivative pairs.

Several sources were employed to conduct this study, including the manufacturers' websites, books devoted to the technical history of the aircraft, industry periodicals, three-view drawings, and airport planning manuals. Only western airliners from the main current and historical OEMs, namely Boeing, McDonnell Douglas, and Airbus, were investigated because there was a reasonable amount of accessible information available for these. The two major regional jet manufacturers, Bombardier and Embraer, usually face similar challenges regarding evolution than the companies studied here, such as retaining commonality while not penalising performance too much, and incorporating new technologies into existing airframe architectures. They therefore often respond in similar ways (i.e. stretching tubular fuselages, re-engining existing designs, and many others). However, there are also some unique challenges that regional jet manufacturers face, such as a larger number of competitors in a smaller market segment [5] and providing comfort approaching that of larger airliners, while meeting the unique operating cost demands of regional operators [6]. Therefore, studying evolvability and design reuse in their products deserves separate attention and is reserved for future work.

Also, only aspects that would normally be considered at conceptual design, i.e. the airframe major components, and the airframe-propulsion integration, were investigated. Freighters and special variants were generally excluded but do receive some mention in the text.

The rest of this paper is organised as follows: first, in the next section, some background on the concept of evolvability is provided, along with a discussion on enablers for evolvability. Section 3 covers the case studies for Boeing aircraft, Section 4 covers McDonnell-Douglas aircraft, and Section 5 is devoted to Airbus aircraft. The results of the studies are collated in Sections 6, 7, and 8, which respectively cover investigations into i) the evolution of payload and range for the different aircraft, ii) modifications by payload-range modification objectives for the derivative, and iii) the maximum changes achieved in important design parameters. Finally, conclusions are drawn in Section 9.

2 Background

2.1 The Concept of Evolvability

Evolvability is a type of change 'ility'. Ilities are desired life-cycle properties of an engineering system that are not intended to fulfil primary functional requirements [1] but which, nonetheless, often constitute much of the value of the system. It is therefore important for designers to recognise what ilities are required and to what extent these must be present in their products. Other change-related ilities include 'flexibility', 'adaptability', 'versatility', 'robustness', and the like. Along with evolvability, these are often grouped under a collective ility, called 'changeability' [7, 8, 9]. Evolvability can be thought of as changeability of the *design* rather than that of the instance (i.e. the physical manifestation) of the system.

2.2 Evolution as a Phenomenon in Aircraft

Whether it was planned or not, many aeroplane designs have undergone substantial evolution. This is true for military, civil transport, and business aviation aeroplanes, as well as some general aviation aircraft. Evolution could manifest through major redesign, such as devising a new wing or much smaller, incremental changes, such as incorporated in 'Performance Improvement Packages' (PIPs – see for example Refs [10, 11, 12]). PIPs, employed extensively by both Airbus and Boeing, are concerted efforts to refine existing designs. These refinements often include aerodynamic improvements (replacing some components with lower drag alternatives, adding winglets, and others), flight control advances (usually through software upgrades), and weight-reduction measures (e.g. lighter cabin equipment and furnishing), amongst many others.

Examples of design reuse and change can be observed from the earliest days of aviation. The Wright Brothers, for example, regularly reused specific features or components on their aeroplanes. For the 1905 Wright Flyer III, the first 'practical aeroplane', they reused the actual engine and most of the metal hardware from the Flyer II [13]. They also re-adopted the wing camber of their famous 1903 design [13]. However, the structure was stronger, the tail taller, the control surfaces featured more area, and the aircraft sat higher above the ground than its predecessors [13].

The Douglas Company, perhaps the most successful American aircraft manufacturer before the jet age [14], also exploited evolvability in their designs. The design of the DC-1 (Douglas Commercial 1) was reused and modified to create the larger DC-2 and, ultimately, one of the most important civil aircraft ever – the DC-3. To devise the DC-2, the fuselage of the DC-1 was 'stretched' (lengthened by introducing extra frames) [14, p. 162] – a practice that has become widely used. The modifications to the DC-2 to create the DC-3 were much more substantial. The fuselage was widened and stretched; the wings were made stronger and longer; the undercarriage was strengthened; and the tail-surfaces were enlarged. The similarities, however, remain unmissable.

All later Douglas propeller transport designs descended from these aircraft and the DC-4, DC-6, and DC-7 were particularly close relatives. The DC-6 was a stretched version of the DC-4 [14, p. 397], whereas the DC-7, in turn, was a stretched version of the DC-6 [p. 469]. In both cases, new technology was incorporated – the DC-6 was the first Douglas transport aircraft that featured a pressurised cabin [14, p. 397]) and the DC-7 featured new materials (particularly titanium in the engine nacelles, increasing fire-resistance) and more powerful engines (the 3,250 horsepower Wright R-3350 Turbo-Compound engines, featuring an exhaust-driven turbine that was connected to the crankshaft) [p. 469].

Several case studies of evolution in military aircraft exist in the literature. These include studies involving fighter aircraft, helicopters, and bombers (see for example Lim [15, p. 41] and Long and Ferguson [16]). These studies on military aircraft evolution are insightful and important. Indeed, unlike transport aircraft, new roles are frequently defined for military aircraft, as novel and unique threats arise constantly. However, as will hopefully become clear in this paper, many civil transport aircraft have also, like their military counterparts, undergone considerable evolution through many innovative advances and therefore warrant study. Surprisingly, a comprehensive and cohesive account of the evolution of civil transport aircraft designs could not be found in the literature[4]. This work contributes to resolving this issue, and is intended to support research that involves the development of techniques to enhance evolvability. Before proceeding to the case studies, a short overview of enablers for evolvability is provided below .

2.3 Enablers for Evolvability

Naturally, much research has been devoted to identifying enablers for enhancing changeability in general. Many of these are directly applicable to the more specialised concept of evolvability. The literature on this topic is vast and there is much overlap. Industry guidelines are often used and constitute lessons

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[4] A comprehensive study covering the changes of commercial aircraft architectures from the Douglas DC-3 to the Boeing 787 have recently been published by Kellari, Crawley, and Cameron [17]. However, this study focuses on architectural changes as a collective and not re-use and commonality across specific designs.

and principles that could facilitate changeability in design [2]. Fricke and Schulz [7] have provided a number of these principles to promote changeability in general. For the current discussion the most relevant are as discussed in the following subsections.

2.3.1 Ideality/Simplicity

Ideality concerns the reduction of complexity and relates to the information axiom of Axiomatic Design (see Suh [18]). [7, p. 358]. Tilstra et al. [19] propose a similar principle, called the ‘parts reduction principle’, in which it is endeavoured to share closely-related functions in modules or parts and using duplicate parts as far as possible. An example of the ideality principle in aeroplanes is the practice of using fuel as a cooling fluid instead of incorporating a dedicated liquid cooling system. This reduces the number of parts and hence the complexity in the system, which makes it easier to change.

2.3.2 Independence

This principle involves ensuring/attempting that each system function is satisfied by a separate design parameter (or subsystem, component, or part). It ensures that change propagation remains limited. Note the apparent contradiction with the previous principle – the most appropriate principle between these two would depend on the application.

An example of the independence principle in civil aircraft is the practice of hanging engines in pods under the wing, instead of embedding them inside the wing. If they were to be embedded in the wing, and if it were desired to incorporate new engines, the wing might need to be modified extensively to accommodate the new engines. Another example is the persistent use of the ‘tube and wing’ configuration, where the function of providing lift is separately fulfilled by the wings and the function of carrying payload is fulfilled by the fuselage. These arrangements limit the amount of change that could be propagated when one of the components are modified.

2.3.3 Modularity/Encapsulation

Modularity, being perhaps the most intuitive of the enabling concepts, is studied widely and often cited as a principle to promote evolvability (see for example Refs [19], [20], and [21]). In a modular systems architecture, the functions are clustered into several physical modules, which are loosely coupled with each other [7]. This promotes the reuse of components, modules, and, ideally, large sections of the architecture [7]. Modularity is therefore closely related to ‘commonality’. According to Pirmoradi et al. [22, p. 5], “modularity decomposes functions into independent groups, while commonality clusters the components and functions based on similarity or other criteria”. Subsequently, modularity supports commonality (along with the other principles listed here), but also makes it easier to change individual components/modules. Commonality is discussed in more detail in Section 2.4.

Modularity relates strongly to and supports independence, and vice versa [7]. The example of the tube and wings configuration therefore applies again, where the fuselage (tube) and wing act as separate independent modules.

2.3.4 Scalability

As the name suggests, scalability refers to the ability to increase/decrease specific design parameters, or the number of multiple identical elements [7]. The design parameters could be geometric, such as length, area, and volume, but also non-geometric, such as thrust and power.

Perhaps the most widely used example of scalability in civil transport aircraft is the lengthening (stretching) or shortening (shrinking) of the fuselage to increase or decrease payload capacity. The tubular construction of modern transport fuselages is particularly amenable to this practice, whereas the length of a more aerodynamically optimised, non-tubular fuselage would require considerable more redesign work. As will be discussed in the case studies, the Boeing 737 was perhaps easier to stretch than the rival McDonnell Douglas DC-9, because it had a short ‘fat’ fuselage (seating six passengers

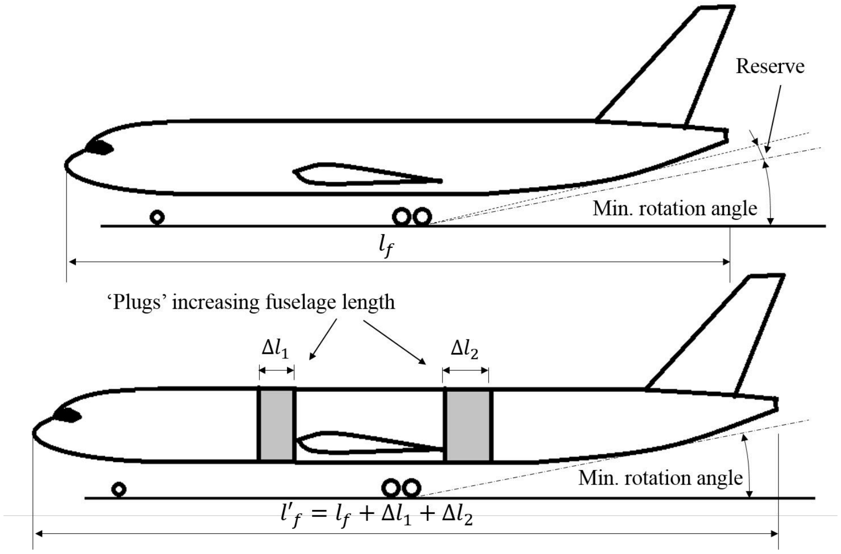


Figure 1: Reserves in undercarriage legs allow lengthening of the fuselage (recreated and modified from Zhuravlev and Zhuravlev [27]).

abreast), which required less lengthening to increase capacity, compared with the five-abreast fuselage of the DC-9.

2.3.5 Redundancy

Redundancy is an essential enabler for evolvability and supports scalability extensively. It may refer to the duplication of certain components within a system architecture, but, for evolvability, it is more often considered as 'excess', 'reserves', or room (margin) for growth. These terms are used interchangeably throughout the text.

Excess is defined by Allen, Mattson, and Ferguson [23, p.] as "a resource, embodied by a system, which is not committed to any of the system's initial set of customer requirements." There are several types of excess (see [23, p. 2]), but for the current discussion the most relevant are excess in geometrical parameters, i.e. length, area, and volume (space) and structural strength. Several authors have quantified excess (see for example [23], [24]) and shown that it is fungible (i.e. different types could be traded off with each other) [16]. A framework that could be used to trade off different types of excess is from Guenov et al. [25]. In that paper, the word 'margin' is employed, but the approach would apply equally to excess.

Examples in aircraft design are plentiful and excess is perhaps the most widely used enabler in the aircraft manufacturing industry. For example, Raymer [26, p. 853] points out that the undercarriage of new aircraft is often designed with an increase of 25% in gross weight in mind. Zhuravlev and Zhuravlev [27] have also written specifically about reserves to facilitate creating derivative passenger aircraft. They state that reserves in wing area and undercarriage length are particularly 'reasonable', because it is exceedingly difficult to change these [p. 175]. Longer undercarriage legs, in particular, provide reserves for the rotation angle at take-off, which allows the fuselage to be made longer (see Figure 1). It also allows for larger engines to be fitted to the design for subsequent variants. Conversely, Zhuravlev and Zhuravlev state that reserves in fuselage volume, fuel tank capacity, structural strength, and engine thrust are not necessary as these could be changed easily [p. 175]. According to them, it is particularly 'easy' to implement local reinforcement to increase structural strength and volume is usually available to incorporate additional fuel tanks. The findings of the case studies that follow seem to support these claims.

2.3.6 Other enablers

For evolvability, Beesemeyer [21, p. 164] adds to the above the principles of 'Leverage Ancestry' (incorporating successful design choices from previous generations); 'Mimicry' (incorporating successful design choices from other systems or domains); 'Disruptive Architectural Overhaul' (modifying large parts of the architecture at a time); and 'Resourceful Exaptation' (adopting design elements from another system or domain and using these for a new purpose). Leverage Ancestry and Disruptive Architectural Overhaul seem to be more relevant at the evolvability exploitation stage (i.e. during the design of the descendant), but could be appropriate when designing the descendant to be more evolvable for future benefit.

2.4 Commonality

The above principles ideally promote design reuse and facilitate change where necessary. As already stated, design reuse constitutes commonality, which often leads to the main benefits of evolvability. Boas [28] states that commonality is the "sharing of components, processes, technologies, interfaces and/or infrastructure across a product family". Commonality could provide many life cycle benefits [29] but the most important for this discussion is that it could potentially reduce development and manufacturing cost.

3 Case Studies in Evolvability: Boeing Aircraft

The world's largest aerospace company [30], Boeing, has a long and illustrious history of producing successful airliners. As will be discussed below, some of their designs have evolved significantly over several decades.

3.1 The progenitor – the Boeing 367-80

On July 15, 1954, a brand-new aeroplane with distinctive sweptback wings and four mighty Pratt & Whitney JT3 turbojet engines took to the skies on its maiden flight [31, p. 164]. This aircraft is the Boeing 367-80. The 367-80 (or 'Dash 80', as it was affectionately known) turned out to be of enormous importance in aviation history and had an airframe layout and design features that can still be seen today on thousands of modern passenger and military transport/tanker aircraft around the world. It can be considered as the de facto progenitor of all Boeing [32] and (arguably) most other jet transports.

The Dash 80 was built by Boeing using their own funding over the period of about two years to test and demonstrate the technologies required for jet transport and tanker aircraft. According to the famous Boeing aircraft designer, John E. Steiner [33], the aeroplane "went on to father the KC-135 military tanker and then the long line of 707 commercial transports". As will be shown, these aircraft went on to serve, to some extent, as baselines for most of the Boeing transports that followed.

3.2 The Boeing 707/720

The changes implemented to the Dash 80 to devise the KC-135 and, subsequently, the 707 were significant. According to Steiner [33], the "KC-135 was a substantially different airplane from the Dash 80" and "gave the engineers a second chance, and as we all know, that can well mean a complete revision". For example, using the Dash 80 as a baseline, Boeing increased the fuselage width for the KC-135 by about 31 cm (for a total width of 366 cm). This was in response to a requirement from the United States Air Force [32, 34]. The plan was to use this fuselage cross-section on the soon-to-follow commercial 707. Such was the case, until the competition, the Douglas Company, won a major order from United Airlines for their DC-8 in 1955 [33, 34]. The DC-8 was to be introduced with a fuselage width of 373.4 cm, which proved to be the main factor in United's decision [33]. In response to this, Boeing was forced to increase the fuselage width of the 707 to 376 cm. This meant that the tooling and jigs for the KC-135

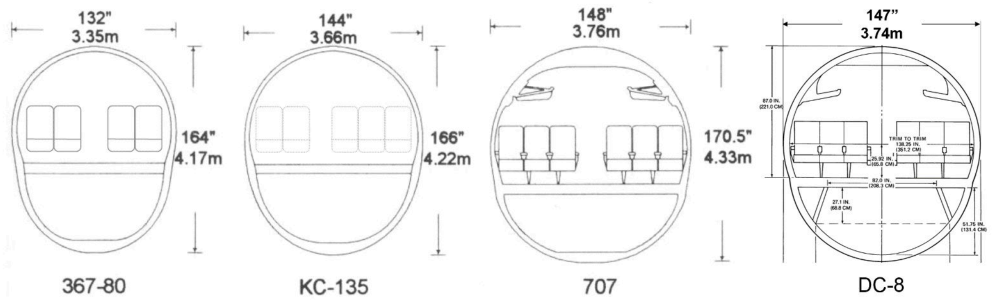


Figure 2: The Boeing 367-80 fuselage cross-section evolution [35]. Used with kind permission of B. Almojuela. DC-8 cross-section added for comparison (used under license agreement with the Boeing Company.)

body could not be reused on the 707, which increased development cost. However, the wider fuselage allowed for a comfortable six-abreast seating configuration and proved to be popular amongst users. These changes are illustrated by the fuselage cross-section drawings of the 367-80, KC-135, and 707 models in Figure 2.

As can also be seen in Figure 2, the fuselage cross-sections of the 367-80, KC-135 and 707 are of 'double-bubble' (also called double-lobe) design, with a distinct upper and lower lobe. As will be illustrated in the subsections on the Boeing 727, 737, and 757 that follow, the upper lobe dimensions of the 707 were reused on all subsequent Boeing narrow-body designs.

Though the fuselage width was altered substantially, the nose shape and cockpit structure remained little changed across the Dash 80, KC-135, and 707. The nose cone was, however, "longer and more pointed" than that of the Dash 80 [34]. Such reuse of the forward fuselage segment design (especially the nose and cockpit dimensions) across aircraft family members and generations is a widely-used practice. The obvious reason for this ubiquity is that the forward fuselage segment design, manufacturing, testing, and certification processes are usually much more expensive and time-consuming than most of the other fuselage segments. This is because of the more complex geometry of the nose (requiring extensive aerodynamic and structural analysis and testing, as well as expensive tooling); the presence of large 'cut-outs' for cockpit windows and doors, incurring structural penalties; and the need for special tests, such as for bird-strikes; amongst others. The aerodynamic advantages that could be gained from revising the nose shape are outweighed usually by the penalties in development cost and time. Indeed, the nose/cockpit design of the 707 was reused to a large extent on the subsequent 727 and 737 families and is still employed on the latest 737s produced today.

Many design updates to the 707 appeared in quick succession in the late 1950s. As will be explained below, it seems that many of these changes were not planned from the outset and rather demonstrated Boeing's (remarkable) responsiveness to the actions of the competition and the needs of its customers. The major different 707 versions are summarised in Table 1 and are discussed next.

The first version of the 707 was the 181 passenger 707-120. Apart from having a wider fuselage than the 367-80 and KC-135, as discussed above, it was also longer than both. The wing geometries of the KC-135 and 707-120 were almost identical. These were also mostly the same as that of the Dash 80, apart from a five-inch (12.7 cm) wingtip extension on each wing to increase the span to 40 m. However, the wing structure was changed from the KC-135 to better suit airline operations [33] – further reducing commonality with the military model. The -120 and KC-135 wings also featured the addition of retractable leading edge flaps, called Krüger flaps, in between the engines. These considerable changes from the Dash 80 and KC-135 constitutes an example of 'disruptive architectural overhaul' (see Section 2.3). They were costly to perform, but enabled the 707 to be a more suitable baseline for further development.

Despite this, a significant set of modifications to the early 707-120 design had to be devised to increase its competitiveness, resulting in the Boeing 707-320 and -420. These aircraft were the 'intercontinental' versions (whereas the -120 was the 'transcontinental' version). The only major difference between the

Table 1: Major variants of the Boeing 707 family.

Variant	First flight [36]	Payload [kg][a]	Range [km][a]	No. sold [b]	Description
707-120	20/12/1957	13,015 [37]	6,308 [37]	56	First production 707.
707-120B	22/6/1960	13,015	6,630	72	707-120 incorporating turbofan engines and design improvements from the Boeing 720.
707-130				7	Extended range version of the -120. Fuselage shortened by 3.05 m [34].
707-130B				6	707-130 incorporating turbofan engines and design improvements from the Boeing 720.
707-220				5	Airframe identical to the 707-120, but features more powerful engines.
707-320	11/1/1959	13,395	7,023	69	Stretched derivative of the 707-120 with longer range. Significantly revised wing along with other airframe changes.
707-320B	31/1/1962	13,395	9,260	174	707-320 design incorporating turbofan engines. Wing was a significantly revised -320 wing: Krüger flaps added along most of the span; trailing-edge flaps modified near the wing root; different wingtip introduced, which increased span [36].
707-320C	2/5/1963 (first delivery)	13,965 [38]	9,260 [39]	337	Mixed cargo/ passenger or full cargo version of the 320B [36]. Cargo door added and floor strengthened [40]. Most widely operated 707 family member.
707-420				37	Identical to the -320, but with Rolls-Royce engines.

[a] Boeing [39], except where otherwise indicated.

[b] Boeing [41]. Includes cargo variants; excludes military models.

-320 and -420 was the engines employed.

The conception of the 707-320 resulted mainly from the need to (again) compete with the DC-8 [34, 33]. The DC-8 design had a larger wing area and higher gross weight than the early 707 designs, which enabled it to cross the Atlantic non-stop — something the 707 could not do [33]. In 1955, Pan Am indicated that they preferred the DC-8, which resulted in Boeing frantically modifying the early 707 design to create an intercontinental version (i.e. the -320).

The -320 was about 2.57 m longer than the -120 [31, p. 169]. It also featured a larger wing area, which was achieved through inserting 'root insert' and outboard span-extending plugs [35]. The wingtips were also altered, and the engines placed such that they protrude further forward [34]. The wing planform was further changed by revising the inboard trailing edge through a modification of the rear spar and a different inboard flap arrangement [35]. These changes are highlighted in the comparison of the wings of the Dash 80/707-120 and 707-320 shown in Figure 3 (also shown is the wing of the later 720 model, which is discussed later). These wing changes could also be considered as disruptive architectural overhaul. Other notable airframe changes included a tip-extension for the tail fin to improve yaw stability. This tip extension was made standard and later retro-fitted on all 707 models [34, p. 38].

3.3 The 720

In 1960, the 707 was followed into airline service by a shorter range, but similar-looking derivative, called the 720 [31, p. 169]. The fuselage of this model was 0.51 m longer than the 707-130 [43].

With the 720 came further airframe enhancements, especially to the wing. Using the -120 wing as baseline, a 'glove' (a leading-edge extension wrapping around the leading-edge of the aerofoil) was added between the fuselage and the inboard engine (see Figure 3) [34]. This increased the wing thickness and sweep, and allowed Krüger flaps to be added inboard of the inboard engine [36]. The glove had the effect of increasing the wing area, which improved low-speed performance, whereas the higher sweep allowed for higher maximum speeds [44]. The structure was lighter and the model had lower fuel capacity [31, p. 169].

From 1960, the more efficient and quieter turbofan engine was made available on all 707/720 models. Models which were powered by these were identified by a 'B' designation suffix. For example, a 707-120 with turbofans was designated '707-120B'. The 707-120B/138B models also received the same aerodynamic enhancements and inboard Krüger flaps as the 720 [36].

Many other 'smaller' design changes were applied to the 707/720 airframe during its illustrious career, which included the creation of cargo versions (not covered here). The 707/720 family was very successful, with a total number of 725 commercial models (of all versions) delivered between 1957 and 1994 [45]. Much of this success could likely be attributed to the experience that Boeing acquired with the Dash 80.

3.4 The Boeing 727

The 707 was followed into service by a more 'unconventional' configuration (for the time), called the 727, which first flew on November 27, 1962 [46]. With 1,832 aircraft delivered between 1964 and 1984, the 727 was even more successful than the 707. It was a smaller aircraft and was designed to operate from relatively short runways and on shorter routes. Like the 707 and 720, it had highly swept wings (although the wings were of a new design), but, instead of the conventional empennage (i.e. low-mounted horizontal tail), it donned a T-tail, along with three fuselage-mounted turbojets. The 727 therefore had a distinctively different airframe configuration than the 707 and 720.

Yet, some of the design was still noticeably common with that of the 707/720. For example, they had nearly identical nose sections. The fuselage cross-section above the floor (i.e. the top lobe) was also kept the same. Furthermore, the 727 fuselage cross-section was also employed on its intended replacement, the Boeing 757, which was introduced into service in 1983. These are all good examples of the evolvability principle of mimicry. The 757, however, used a new nose section to maintain commonality

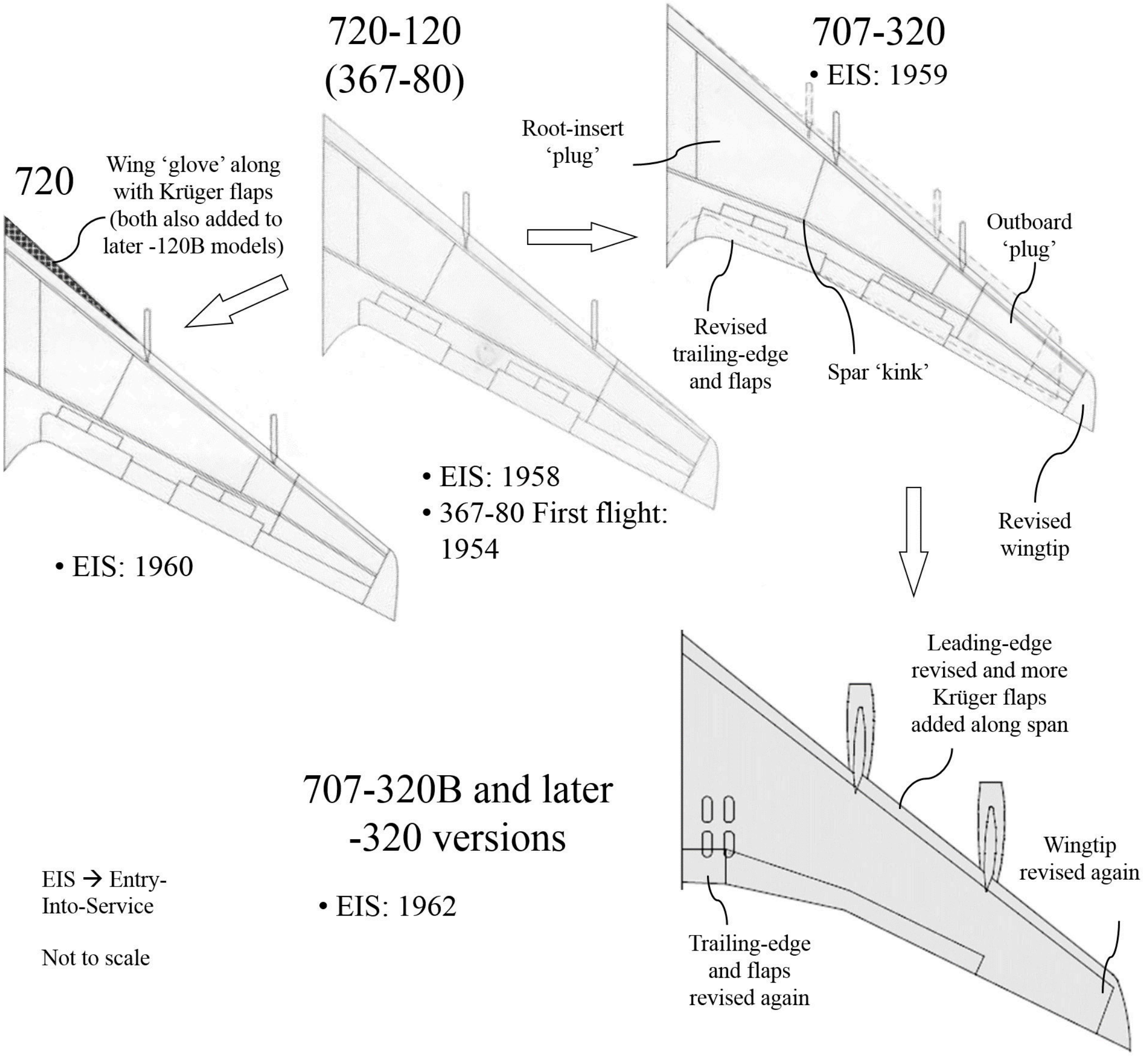


Figure 3: Boeing 707 wing evolution (used and adapted with permission from Almojuela [35] and Boeing CAD drawings [42] (for the -320B) [used under license agreement with the Boeing Company], EIS dates from [43]).

Table 2: Major variants of the Boeing 727 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
727-100	9/2/1963 [47]	10,070	3,817	551	Basic original version.
727-200	27/7/1967 [47]	12,730	2,778	1,260 (Incl. Adv)	Stretched derivative of the -100.
727-200 Advanced	1971/72 [47]	12,730	4,334	(Incl. in -200)	Improved 727-200. Thicker wing skins and strengthened undercarriage [31, p. 177].

[a] Boeing [39].

[b] Boeing [41]. Includes cargo variants; excludes military models.

with the Boeing 767, which was developed in parallel with it. This is discussed later (see Section 3.7). The variants of the 727 are shown in Table 2.

The first model of the 727 was the -100 model, which was powered by three Pratt & Whitney JT8D engines. To offer increased capacity, Boeing introduced a stretched version, the 727-200, in 1965.

From 1972, an improved -200 version became available, which was designated 'Advanced'. The Advanced 727 had more powerful engines and structural design changes (see Table 2). These enabled more fuel to be carried, which increased range.

As a family of aircraft, the 727 had seen fewer major airframe geometrical changes than the 707/720 family, with only the length of the fuselage changing substantially. The original wing design (especially the high-lift devices) simply sufficed and allowed substantial increases in MTOW. This, in turn, allowed stretching for higher payload capacity, as well as increased range.

3.5 The Boeing 737 Family

The 737 was designed in the early sixties for short to medium ranges and to land on runways less than 1830 m [39, p. 4]. From the beginning, it was aimed to reuse as much as possible of the design of the 727 [48, p. 12]. This would save time and money and make it attractive to existing 707/727 users [48, p. 12]. However, unlike the 707/720 or 727 families, the 737 employed two engines that were wing-mounted. Its configuration was therefore again different from its predecessors. With over 15,000 sold at the time of writing [41], the 737 is the most successful civil jet transport aircraft ever produced.

Along with continuously improving propulsion, the 737 airframe design has undergone significant evolution, with several modifications applied to the fuselage, wings, empennage, and nacelles. The latest version, called the 737 MAX 10, was introduced in 2017 [49] and, although a very different aircraft from the first 737-100, still retains many of the same design features such as the basic fuselage geometry.

The decision to place the engines under the wing was a significant one. Boeing found that using this arrangement would enable the use of a short, wide body and a low horizontal tail [33, p. 14]. The same upper fuselage cross-sections as the previous Boeing jetliners could therefore be employed [43, p. 72] (mimicry). This was a major advantage, as the aircraft would have the same passenger and cargo configuration of the 707 and DC-8 [33, p. 14]. Subsequently, the 737 design could retain a 60% parts commonality with the 727 and 707, predominantly in the cabin and flight deck [32, p. 111].

From an evolvability point of view, another advantage of the engine-under-wing configuration is that the engines are close to the centre of gravity (CoG). This allows heavier engines to be introduced without a large shift in the CoG, which would inevitably occur if heavier engines were to be attached to the rear fuselage [50]. Furthermore, because the wider fuselage enables more seats abreast, a relatively smaller amount of stretching is needed to increase the passenger capacity than would be with fewer seats abreast. Finally, growth was perhaps also made easier by both spars of the 737 wing being kinked. This arrangement provided more room for fuel, which could be exploited later to increase range. Much

Table 3: Major variants of the Boeing 737 Original family.

Variant	First flight [51]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
737-100	9/4/1967	8,075	2,574	30	Original version.
737-200	8/8/1967	9,215	3,704	1,095 (Incl. Adv)	Similar to 737-100, but fuselage lengthened (plugs: 0.91 m fore, 1.02 m aft) [39, p. 5].
Advanced 737-200	1971	9,215	4,630	Incl. in -200	Dimensionally the same as -200 [39, p. 4], but with more powerful engines and higher fuel capacity [31, p. 183]. Featured the use of composite materials in the interior, rudder, elevator, and ailerons [51]. Subsequent improvements applied to increase range and payload. This included the addition of an auxiliary fuel tank and increased gross-weight [51].

[a] Boeing [39].

[b] Boeing [41]. Includes cargo variants; excludes military models.

of the success of the derivatives could probably be attributed to these aspects ([32, p. 110] quoting Jack Steiner), which all promoted scalability.

The 737 family can be divided into four generations. These are the 'Originals', the 'Classics', the 'Next-Generation' (NG), and the 'MAX'. Each of the generations consisted of multiple members, with different payload and range capabilities and are discussed next.

3.5.1 Boeing 737 Originals

The first 737 was the -100 model. It performed its maiden flight on 9 April 1967 [49] and had room for about 85 passengers in a two-class configuration [39, p. 13]. The -100 and all subsequent 'Original' variants were powered by versions of the Pratt & Whitney JT8D turbofans [43, p. 27]. These aircraft also employed flaps and leading-edge devices that were similar to those on the 727 [31, p. 183].

Soon after introducing the 737-100, Boeing started development of the 737-200 as a response to the emerging Douglas DC-9-30 [33, p. 14]. Apart from a longer fuselage, all dimensions remained identical to those of the -100 [39, p. 4]. A further improved variant, called the 737-200 Advanced, was later introduced [51]. The 737 Original family members are summarised in Table 3.

3.5.2 Boeing 737 Classic

With development starting in 1979, the 737 'Classic' family was pursued by Boeing to exploit the much-improved fuel-consumption and low-noise characteristics of the then new CFM56-3 turbofans [43, p. 74]. The first of the Classic members to be developed was the 737-300 (Figure 4), which first flew on 24 February 1984 [52]. It featured a stretch of the -200 fuselage which allowed a maximum seating capacity of 156 passengers [43, p. 74].

Despite the fuselage scalability of the 737 architecure, the changes made to devise the Classics could perhaps be seen as another example of disruptive architectural overhaul. First, the wing was changed substantially. According to Wright [48, p. 26], a wingspan extension using a new centre-section would usually be considered for larger and heavier engines. However, with wing-mounted engines, this would have meant a complete redesign. Boeing wanted to avoid this and resorted to only adding 23 cm span extensions at each wingtip [43, p. 74]. Despite this, from early calculations it was shown that the smaller increase in wing area would not be enough to keep the higher approach speeds (resulting from the higher design weights) within acceptable limits [48, p. 26]. Therefore, a new leading-edge slat was integrated from the engine pylon to the wingtip. The new slat increased the chord over the whole wing by an average of 4%. The resulting larger wing area ensured that the increase in approach speed remained

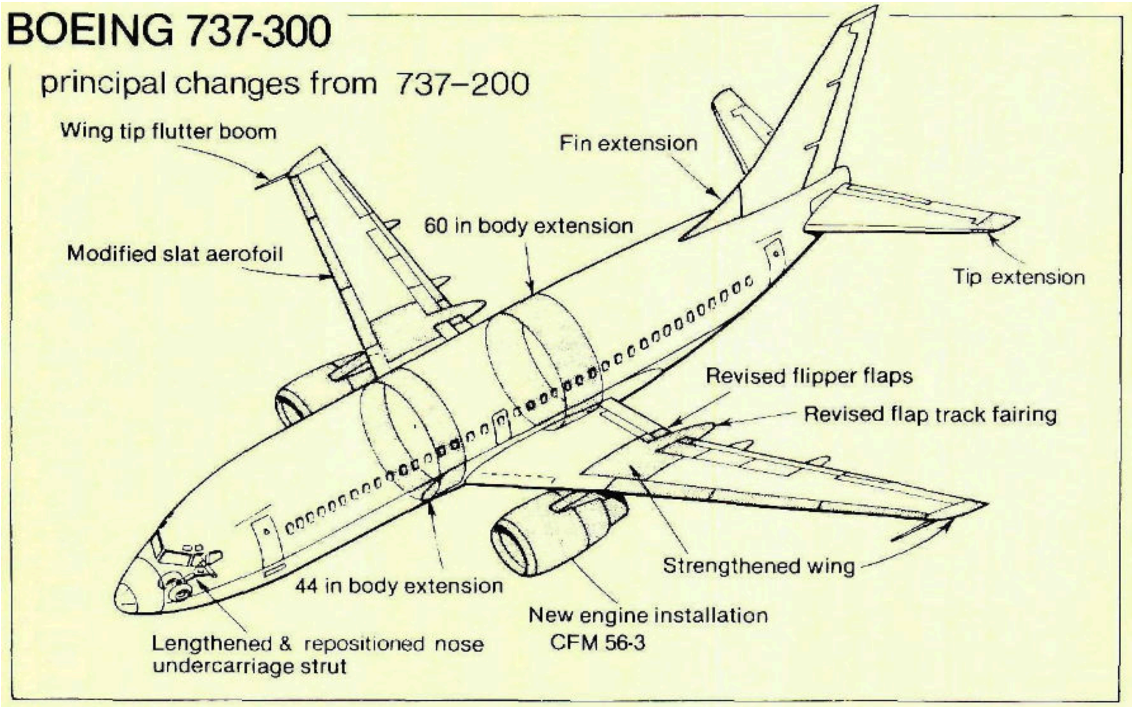


Figure 4: Boeing 737-300 changes from the 737-200 (Flight International, 23 October 1982 – with kind permission of FlightGlobal – part of Reed Business Information Ltd).

below 5 kt [48, p. 29]. The trailing edge flaps where also revised where the -100/-200 engine protruded aft of the wing. So-called 'flipper flaps' were added at this location and the flap track fairings were changed [43, p. 74]].

Empennage modifications included an increase in the vertical stabiliser area [43, p. 74], through the addition of a triangular wedge at the lower leading-edge. The horizontal stabiliser span was increased using tip extensions [39, p. 5], along with an increase in elevator span [48, p. 29].

The nose wheel leg was lengthened for increased engine-ground clearance [48, p. 29]. The main undercarriage could also have been extended to make room for the larger engines, but this would have implied a redesign [48, p. 28]. Therefore, to ensure proper clearance, the engine nacelle was made flat at the bottom (a distinguishing characteristic of the 737 Classics and NG) and the accessory drives were placed on the side of the engines [43, p. 74] [48, p. 28]. The engine was also attached to the pylon such that most of the assembly protruded forward of the leading edge [48, p. 28]. Subsequently, the sections attached to the pylons had to be strengthened. To prevent overheating of the bottom wing surface and trailing edge flaps, the engine was tilted at an angle to deflect the exhaust downwards [48, p. 28]. These modifications solved the clearance problem and provided more room for fuel because the area above the engines could not be used to accommodate fuel in the earlier versions [48, pp. 28-29]. The engine increased in size again with the introduction of the latest version, the 737 MAX (see Section 3.5.4). The evolution in the engine-wing integration is illustrated in Figure 5.

These changes were substantial, but, as stated by Norris and Wagner [32, p. 113], "it was the inherent strength of the original design and the positioning of the engines beneath the wing rather than at the tail that allowed the new developments to take place."

3.5.3 Boeing 737 Next-Generation

In 1991, Boeing started working with more than 30 airlines to develop further derivatives of the highly successful 737 [49]. This led to the 737 Next-Generation (737NG) being launched in June 1993 [49].

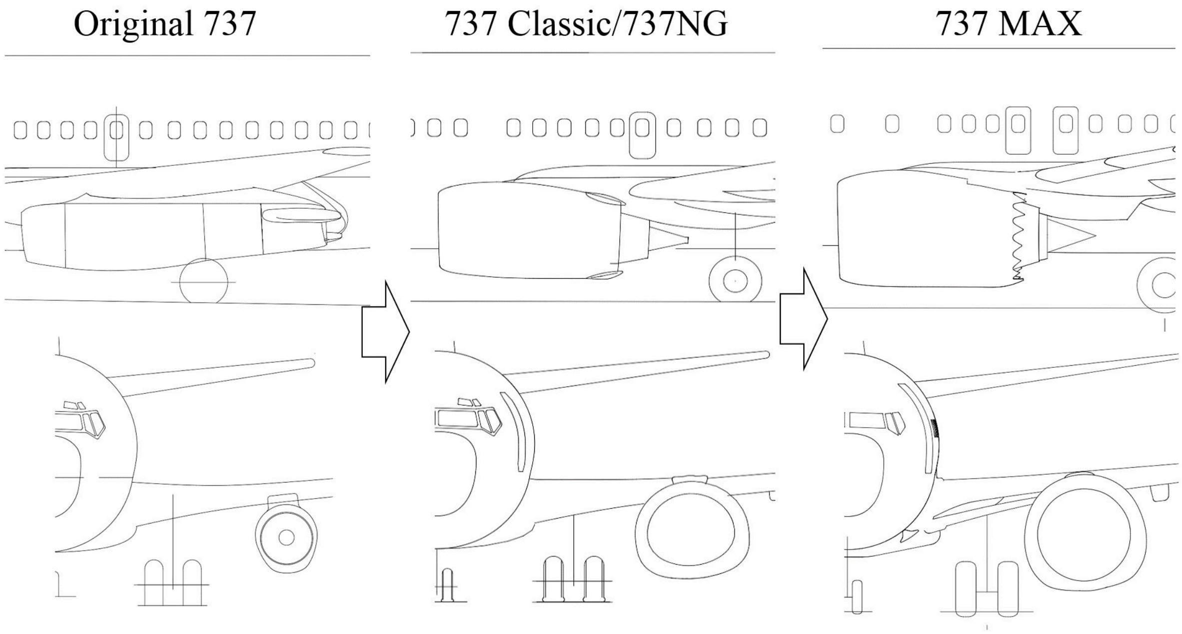


Figure 5: Boeing 737 nacelle evolution (created from Boeing CAD drawings [42] – used under license agreement with the Boeing Company).

Table 4: Major variants of the Boeing 737 Classic family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
737-300	22/1/1998 [52]	12,160	5,186	1,113	Stretched derivative of the 737-200 (plugs: 1.12 m fore, 1.52 m aft) [43, p. 74]. See text for other airframe and propulsion changes.
737-400	19/2/1988 [53]	13,870	4,736	486	Stretched version of the 737-300 (plugs: 1.83 m fore, 1.22 m aft) [39, p. 5]. Additional emergency exits. Krueger flaps added outboard of the engine pylons [43, p. 74]. Uses more powerful version of the CFM56-3 [48, p. 53]. Apart from the fuselage plugs and local strengthening of the structure, the -300 and -400 are almost identical [32, p. 115].
737-500	20/6/1989 [54]	9,215	5,463	389	Fuselage same length as 737-200 [48, p. 53]. Structurally essentially the same as the -300 and -400 [32, p. 116].

[a] Boeing [39].
[b] Boeing [41].

Table 5: Major variants of the Boeing 737NG family.

Variant	First flight [49]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description [39, p. 6].
737-600	22/1/1998	9,215	6,730	69	Same fuselage dimensions as the 737-500.
737-700	9/2/1997	12,160	6,697	1,164	Same fuselage dimensions as the 737-300.
737-800	31/7/1997	15,200	5,847	5,129	Stretched 737-400 fuselage.
737-900	3/8/2000	16,815	3,704	52	A stretched derivative of the 737-800 (1.37 m plug forward, 1.07 m plug aft).
737-900ER	1/9/2006	16,815	5,289	505	Increased capacity, long-range version of -900. Strengthened undercarriage; heavier wing skin gauge; flat aft pressure bulkhead; and additional emergency exits [49].

[a] Boeing [39].

[b] At time of writing (from Boeing [41]). Includes cargo variants; excludes military models.

Boeing capitalised on lessons learned on the then-recent development of the Boeing 777 (an example of mimicry). The resulting product was a new aircraft family in which “20% of airframe spares and 70% of ground support equipment remain common with earlier models” and, within the NG family, 95% of spares were common [55, p. 70].

The changes to the baseline Classic family were not trivial, however. First, the wing area and fuel capacity were increased by 25% and 30% respectively. This was done by means of a 43 cm chord increase [49],[55, p. 70] and a 272 cm semi-span extension at each tip [55, p. 70]; These changes modified the wing’s aerofoil sections. In addition, the CFM56-3 turbofan, used on the Classic variants, were replaced by versions of the more advanced CFM56-7 [39, p. 7]. Blended winglets were made available as an option on later NGs and as retrofit on in-service aircraft [56].

Other modifications included [55, p. 71]: new double-slotted flaps; a new wing-body fairing; upgraded and simpler undercarriage; horizontal tail tip-extensions, a longer elevator; fuselage strengthening applied to handle the larger tail loads and higher design weights; as well as the addition of a root-insert to increase the vertical stabiliser height to 7.17 m. The variants of the 737NG family are summarised in Table 5.

3.5.4 Boeing 737MAX

Boeing launched the ‘737 MAX’ family as a new-engine variant in August 2011 [57]. The engine to be used was to be the CFM Leap-1B [58] and a new nacelle and pylon were designed to accommodate it [59]. The engines are cantilevered higher and further forward than with the NG [60] to retain ground clearance. The nose gear strut was lengthened by 20 cm for the same reason [60].

Apart from the new engines, the MAX family is fitted with new laminar flow winglets, which are of a distinctive ‘split-tip’ type [61]. Other improvements include a re-contoured tail cone to reduce drag, along with numerous other small aerodynamic enhancements [59]. The main landing gear was reinforced, and the fuselage skin was made thicker at some locations [59]. Combined, these improvements were reported to reduce fuel consumption by 14% over 737NG [59].

The MAX, as with its ancestors, have sold very well thus far, with a total number of 5,005 already ordered at the time of writing [41]. It is offered in four versions (see Table 6). These are essentially direct replacements for the NG versions, but the MAX 7 is slightly longer than the -700 and a new capacity variant was introduced as the ‘MAX 10’.

3.6 The Boeing 747

By the mid-1960’s airline traffic grew at more than 15% per year [33, 31]. At the same time, the United States government invited aircraft manufacturers to compete for a contract for the development of a

Table 6: Major variants of the Boeing 737 MAX family.

Variant	First flight	Payload [kg]	Range [km]	Description
MAX 7 (737-7)	16/3/2018 [62]	13,110 [63]	7,130[63]	Slightly longer fuselage than the 737-700 [58] (plugs: 1.17 m fore, 0.76 m aft) [64]. Employs MAX 8 wing and landing gear (to handle higher weights) and features a pair of emergency exits over the wing rather than one. Structural 're-gauging' (thickening) and other strengthening applied [65].
MAX 8 (737-8)	29/1/2016	15,200 [41]	6,556 [41]	Major derivative of the 737-800 [58]. See text for details.
MAX 9 (737-9)	13/4/2017	16,910 [63]		Derivative of the MAX 8 (fuselage based on the 737-900ER). [58]
MAX 10 (737-10)	Launched 19/6/2017 [66]	17,860 [63]	6,112 [63]	1.67 m stretched derivative of the MAX 9 [66]. According to Boeing [67], it will have new levered main undercarriage to ensure adequate margin for rotation at take-off, new emergency exits, new rear pressure bulkhead, and a revised wing.

large military transport to be called the C-5A [33]. Boeing lost to Lockheed, but employed the expertise that they had acquired to devise an aircraft that could meet the rising traffic demands [33, 31]. This aircraft was the 747 'Jumbo Jet'.

On the propulsion side, Pratt & Whitney lost to General Electric for providing an engine for the C-5A. However, like Boeing, this left them open to exploit the expertise they gained to develop an engine for the 747 [33]. This led to the JT9D turbofan being selected to power the 747 [43].

The 747 was (and still is) enormous. It is able to carry ten passengers in a row in a twin-aisle, wide-bodied fuselage – the first jetliner to feature this configuration. The wide fuselage cross-section was driven by the need for a large cargo-carrying deck, under the mistaken belief (at the time) that supersonic transports (SSTs) would soon be the norm and that the 747 would eventually be relegated to only carrying freight. For the same reason, the distinctive 'hump' at the nose resulted from the need to load freight onto the main cabin through the front of the nose [33, 31]. The age of the SST, of course, did not materialise, but the 'wide-body' was here to stay. The 747 turned out to be very successful, with a total of 1,572 aircraft ordered at the time of writing [41].

The go-ahead for the 747 was given on April 15, 1966 [33, p. 16] and the first flight was on the 9th of February 1969 [43, p. 76]. The different variants are summarised in Table 7, followed by in-depth discussions on each. Figure 6 highlights the major changes across the variants.

3.6.1 747 Classics

The first 747s were the 747-100 and 747-100SR. These were soon followed by the 747-200B. The 747-200B was almost identical to the basic -100, but carried more payload, featured longer range, and had more powerplant options.

The 747SP (Special Performance) was a long-range variant of the 747-100, with the fuselage shortened by 14.6 m [43, p. 76]. It has the same tank capacity as the -200B but accommodates only about 288 passengers [43, p. 76]. The shrink was not entirely straightforward. A fuselage section had to be removed forward of the front spar, as is usual for shortening a fuselage, but the upper section just aft of this had to be removed as well, to make room for the rear part of the hump there [32, p. 140]. A revised centre section, to lower mass, along with a new, smaller wing body fairing was also incorporated. To replace sections that were removed ahead of the rear-pressure bulkhead, a new aft fuselage section had to be designed [32, p. 140]. In addition, the fuselage was made lighter in certain areas.

The tailfin was about 1 m lower at its base (because of the new aft fuselage section), but received a

Table 7: Major variants of the Boeing 747 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
747-100	9/2/1969 [43, p. 76]	44,082	7,408	175	Original basic version.
747-100SR	Introduced: 1973 [43, p. 76]	51,756	3,704	29	Short-range ('SR') variant of the -100. Strengthened airframe for more frequent landings [31, p. 202].
747-200	11/10/1970 [68]	44,082	11,297	316	Higher payload/longer-range derivative of the -100. Overall dimensions same as -100. Stronger structure, with thickened skins. Strengthened wing spars, landing gear beams, flaps, and rib-and-wing panel splices [66]. The fuselage has a strengthened keel beam, gear supports, stringers, skin, and door frames [66]. Local reinforcement of the landing gear was applied and new nose tires were employed [66]. The empennage was made stronger by making changes to the torque box and centre section [66].
747SP	4/7/1975 [69]	30,905	11,112	45	Long-range, shorter-body variant of the -100. See text for details.
747-300	5/10/1982 [43]	47,120	10,186	81	Derivative of the -200 with stretched upper deck, but with similar gross weights and engines [43, p. 78].
747-400	29/4/1989 [70]	47,120	12,594	694	Derivative of the -300 with significant changes made to structure and systems. The wing-body faring was recontoured and an extra wing leading edge flap was added [66]. A fuel tank was incorporated in the horizontal stabiliser [66]. Wingtip extensions were fitted along with new winglets [32, pp. 140-141].
747-8	3/2011 [71]	48,925	13,483	47	Major derivative of the -400. Stretched fuselage and substantially revised wing, along with other modifications (see text for details).

[a] From Boeing [39].

[b] At time of writing (from Boeing [41]). Includes cargo variants; excludes military models.

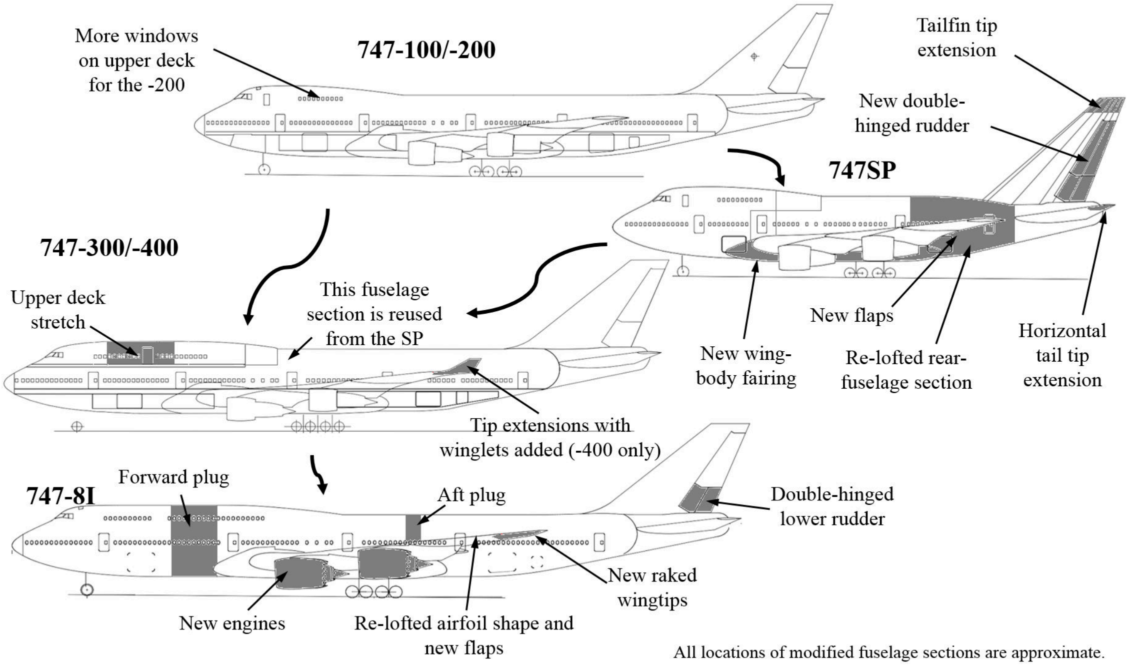


Figure 6: Major changes across Boeing 747 variants (created from Boeing CAD drawings [42] – used under license agreement with the Boeing Company).

1.52 m tip-extension and a double-hinged rudder to account for the smaller moment arm arising from the shorter fuselage [32, p. 140]. The horizontal stabilizer span was also extended by 1.52 m [32, p. 140] through tip extensions.

The wing remained similar to that of the 747-100. However, the structural gauges of the wing-box and carry-through structure ribs, spars, and stringers were reduced to make the wing lighter [32, p. 140]. The trailing-edge flaps were replaced with simpler, single-slotted flaps [32, p. 140].

The magnitude of these changes illustrate that ‘scaling down’ is perhaps generally more difficult to achieve than ‘scaling up’ and often involve disruptive architectural overhaul. Other scaling-down examples, such as the Airbus A300 to A310 further support this notion.

3.6.2 747-300 and 747-400

By the late seventies, stretching of the 747-100/-200 had been considered but, eventually, only an upper deck extension of 7.11 m was adopted by 1980 [43, p. 78]. The new version to incorporate this longer upper deck was called the 747-300, which first flew on the 5th of October 1982 [43, p. 78].

A significantly improved derivative of the 747-300 was launched in October 1985 [43, p. 78]. This aeroplane was designated the 747-400 and much of the experienced gained with the then recently developed Boeing 757 and 767 was employed in its development [32, p. 140] (further examples of mimicry). Although having the same overall dimensions (except for span), major changes were made to the -300 Baseline. These involved the addition of winglets, along with substantial revision of the structure and aerodynamics (see Table 7). The winglets improved aerodynamics, while keeping the span within operational limits [72, p. 72]. Despite the increased span, the use of new alloys in the wing structure made it about 11% lighter than the -300 wing [72, p. 73]. These modifications improved fuel economy and lowered operating costs, and the -400 became the best-selling version of the 747 [32, p. 141].

3.6.3 747-8I

A major new variant of the 747, the 747-8, was announced on November 14, 2005 [71]. The '-8' indicates that the new 747 bears a strong relation with the 787 – it employs versions of the 787's GEnx engines, the 787's 'sawtooth' nacelles, and the 787's raked wingtips [71]. These are excellent examples of successful mimicry and demonstrate how a certain product could evolve from different ancestors (in this case, from both the 747-400 and 787-8).

To devise the -8, the -400 fuselage was stretched by means of inserting two plugs (4.10 m in front of the wing and 1.5 m aft). This was the first time the 747 was stretched and, at 76.3 m, currently makes it the longest commercial passenger aircraft in the world [71].

With the introduction of the -8 also came the most substantial modifications to the original 747 wing. The outboard wing was relofted, i.e. the aerofoil shape changed, but the basic structural layout was kept the same [73]. This new loft smooths into the original shape where the wing meets the fuselage in order to keep the centre-section geometry the same [73]. The relofting improved L/D and altered the lift-distribution, which helped improve structural efficiency [73]. Thicker aerofoil sections were employed, which did not impose a drag penalty, because of advances achieved in aerodynamics since the original 747 was introduced [73]. The flaps were changed to double-slotted inboard and single-slotted outboard and redesigned flap tracks and fairings were fitted [73]. As already mentioned, the 787-style raked-wingtips were adopted as well [73].

Other significant changes included new main undercarriage wheels, tires, brakes, and trucks [73]. A double-hinged lower rudder was introduced to increase yaw control authority. Materials from both the 777 and 787 programmes were adopted [73].

The 747-8 is a very modern aircraft, yet much advantage was gained by deriving it from the 747-400 (and taking advantage of lessons learned from the 777 and 787 programmes).

3.7 The Boeing 757 and 767 Family

According to Steiner [33], in the early seventies, Boeing studied how advances in technology, such as more efficient engines, improved Aluminium alloys, composite materials, superior avionics, and more efficient wing designs could be incorporated into existing aircraft, such as the 727. By 1975, however, they came to the conclusion that a requirement existed for an all-new aircraft, with a capacity of 200 passengers and a range of between 2000 and 2,500 nautical miles. This led to design work starting for the clean-sheet Boeing 767 in 1978, by which time it was also clear that a slightly smaller aircraft with shorter range was also required [33]. Subsequently, the '757' designation was reserved for the smaller sister, which was to replace the 727. The 757 was given the go-ahead in 1979 [33].

Commonality between the 757 and 767 was an important factor in the design. According to [31, p. 246], Boeing claimed that the 767 is "42.8 percent identical to the 757, [and] 19.7 percent similar." Common parts and systems included part of the vertical tailfin, the flight deck control panel, the electrical, hydraulic, and air conditioning systems, as well as the auxiliary power unit [74].

In an exemplary case of providing excess to promote scalability, the wing designs of these aircraft were provided with substantial planform area, to ease stretching of their respective fuselages in the future [75]. The 757 wing root-chord was also wider than needed, which allowed accommodating an unusually long landing gear. The longer gear increased clearance for larger engines but also left ample margin for stretching the fuselage [32, p. 150]. This decision was based on lessons learned from the 707, where the gear of that aircraft was designed to be short to save weight but resulted in the 707 not being adequately amenable to much stretching [32, p. 150]. For the same reasons, the kink in the wing of the 767 was further outboard, which increased wing area and left adequate margin for growth [32].

3.7.1 757

The 757 employed the fuselage cross-section of the 727 [43, p. 80], but had a new wing. Originally, the design also incorporated the 727 nose, but, because of the decision to maintain cockpit commonality with the 767 [43, p. 80], the windscreen was changed to a curved design. This necessitated a new tapered

Table 8: Major variants of the Boeing 757 family.

Variant	First flight [76]	Payload [kg][a]	Range [km][a][39]	No. sold[b]	Description
757-200	9/2/1982	17,671	6,667	994	Basic variant.
757-300	2/8/1998	22,705	5,926	55	Stretched 757-200 (plugs: 4.06 m fore, 3.05 m aft) and strengthened wings, pylons, undercarriage, and new wheels [77].

[a] Boeing [39].

[b] Boeing [41]. Includes cargo variants; excludes military models.

Table 9: Major variants of the Boeing 767 family.

Variant	First flight [78]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
767-200	26/9/1981	20,457	7,408	128	Basic model.
767-200ER	6/3/1984	20,457	12,205	121	Derivative of the -200. Centre-section fuel tank added.
767-300	30/1/1986	25,900	7,408	316	Stretched derivative of the 767-200ER (plugs: 3.07 m fore, 3.35 m aft) [43, p. 85]. Parts of wing and fuselage skin thickened and undercarriage legs strengthened [43, p. 85].
767-300ER	9/12/1986	25,900	11,112	583	Higher gross-weight variant of the -300, with additional fuel capacity and airframe strengthening.
767-400ER	9/10/1999	28,120	10,186	38	Stretched derivative of the 767-300ER (plugs: 3.36 m fore, 3.07 m aft) [78]. Strengthened airframe [78] and longer main landing gear. 767-300ER engines, nacelles, and struts employed [79]. New, raked winglets. Strengthened wing box (thicker ribs, spars and skin) [79][78]; new main undercarriage featuring longer legs and new brakes and new tyres [79],[80]. Fuselage structure strengthened to withstand higher bending loads [80].

[a] Boeing [39].

[b] At time of writing (from Boeing [41]). Includes cargo variants; excludes military models.

forward fuselage section between the flight deck and constant fuselage sections [75]. In addition, the nose shape was now completely new and unique amongst Boeing jetliners. Early concepts for the 757 also sported the T-tail of the 727, but the advantages to be gained from commonality were nullified as the new aircraft's stability and control requirements diverged from the previous design. The horizontal tail was therefore moved to the more conventional lower location, to increase commonality with the 767 [75]. Therefore, mimicry (across the 727 and 757) was sacrificed for increased commonality with another product.

There were two major variants of the 757, the 757-200 and 757-300, which are listed in Table 8. There was also an earlier 757-100 design, but this was abandoned.

3.7.2 767

The 767 first flew on 26 September 1981 and was produced in several versions, summarised in Table 9 and the text below. Originally, (as with the 757) a shorter fuselage length option, the 767-100, was offered, but, owing to a lack of orders, this model was dropped [43, p. 82].

The first 767 was the 767-200. An extended range (ER) version followed, which was created by increasing the gross-weight and modifying the carry-through structure to act as a fuel tank [75]. This enabled the -200ER to fly on transatlantic services. The next variant, the 767-300, was a stretched version of the -200, with a slightly strengthened airframe. With the later 767-300ER, extra fuel capacity was made available in the centre section, and higher thrust engines were incorporated [78] [43, p. 85]. The gross weight was increased again for this variant and further structural reinforcement was applied [78]. The final, longer-range 767 variant, the 767-400ER, is a stretched derivative of the -300ER and features new raked winglets, which extended the wingspan [79],[80].

3.8 The 777 Family

The Boeing 777 was originally intended to be introduced directly after the 767, as part of a trio of closely-related products that also included the 757 [81]. It was to have three engines and was conceived to compete with the McDonnell Douglas DC-10 and Lockheed L1011 [81, 82]. However, Boeing delayed the 777 and it was only on the 29th of October 1990 that it was finally launched as a brand new aircraft to fill the gap between the 767 and 747 and compete with the Airbus A330/A340.

A new circular fuselage cross-section with a large diameter of 6.2 m was adopted [83, p. 35]. This was different from all preceding Boeing jetliners, but the nose geometry of the 767 was reused [84].

Norris and Wagner observe that the wing was large, with substantial room for fuel [83, p. 36]. The distinctive six-wheel bogie main undercarriage design allowed the aircraft weight to be spread more evenly on runways and taxiways [p. 40]. The lower 'pavement loading' would allow for growth versions, without having to add an extra leg, as was needed for the DC-10-30 when it was derived from the DC-10-10 baseline [p. 40]. However, the nose gear design remained similar to that of the 767 [p. 41].

Although being a new aeroplane, the valuable experience gained from previous projects was exploited fully in another exemplary case of mimicry. For example, the Structures Chief Engineer on the 777 programme, Larry Rydell (as quoted by [32, p. 170]), described the 777 wing box as a "carbon copy of the 767 philosophy".

With over 2,000 orders at the time of writing [41]), the Boeing 777 has become very successful and several variants exist or are in development (see Table 10). The 777-200 was the basic medium-range version and the -200ER is the extended range version. The 777-300 was launched on the 26th of June 1995 and features a 19-frame stretch of the 777-200 fuselage [85]. According to a former -300 programme manager, Jeff Peace (as quoted in [32, p. 173]), the 19-frame plug was decided on, as it provided a satisfactory trade-off between take-off rotation angle and take-off speed. This enabled the same main undercarriage to be employed.

Ultra-long-range versions were studied by Boeing from the start of the 777 programme [84] and eventually led to the combined launch of the 777-300ER and 777-200LR on the 29th of February 2000 [85].

Both the -200LR and -300ER have increased fuel capacity with added centre and rear-cargo hold fuel tanks [85]. The -200LR has the same fuselage length as the -200 and -200ER, whereas the -300ER has the same length as that of the -300. External airframe changes were made, however, the most discernible being the addition of 'raked' wingtip extensions to both variants [85]. Furthermore, more powerful versions of the GE90 powerplant are employed on both the -200LR and -300ER [85].

Because of the combination of the longer fuselage and high operating weight, the -300ER features more substantial revision to the main landing gear than the -200LR. It incorporates a semi-levered actuator that maintains the bogie-fuselage angle in such a manner that the aircraft can pivot on the rearmost wheels at rotation during take-off (see Figure 7). This increases the allowable rotation angle, which lowers the required take-off speed and distance [88]. In addition, the nose gear on the -300ER had to be made extendable [85].

A substantial 777 derivative programme, the '777X', was formally launched in November 2013 [89]. The new family would consist of the 400-seat '777-9', the long-range '777-8', and the '777X Freighter'. The 777-8 will be a replacement for the 777-200LR [90] and is intended to have a range of 8,690 nm (16,090 km) [87], but with the two-class seating capacity of the 777-300ER [90], [87]. It will be a

Table 10: Major variants of the Boeing 777 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
777-200	12/6/1994 [85]	28,975	9,816	88	Original basic variant.
777-200ER	7/10/1996 [85]	28,975	13,890	422	Extended range derivative of the -200. Additional fuel capacity in the centre-section tank. Strengthened wing, fuselage, undercarriage, and engine pylons.
777-200LR	15/3/2005 [86]	28,975	18,520	60	Ultra-long-range derivative of the -200ER. More fuel capacity, raked wingtips added, stronger structure, and higher thrust [85].
777-300	16/10/1997 [85]	34,960	10,455	60	Stretched derivative of the -200/-200ER (plugs: 5.33 m fore, 4.8 m aft) [85]. Strengthened inboard wing and landing gear [85]. Airframe skin and keel beam strengthened [32, p. 173] to endure higher body-bending loads.
777-300ER	24/2/2003 [85]	34,960	14,686	844	Long-range derivative of the -300. Strengthened airframe, more fuel capacity and raked wingtips added. Substantial revision of the undercarriage (see text). Higher thrust.
777-8	N/A	34,675 [87]	16,094 [87]	Incl. in -9	Shorter derivative of the 777-9.
777-9	N/A	39,330 [87]	14,141 [87]	326 (incl. -8)	Major stretched derivative of the 777-300ER. New wing and other substantial revisions to the airframe, along with new engines.

[a] Boeing [39], except where otherwise indicated.

[b] At time of writing (from Boeing [41]). Includes cargo variants.

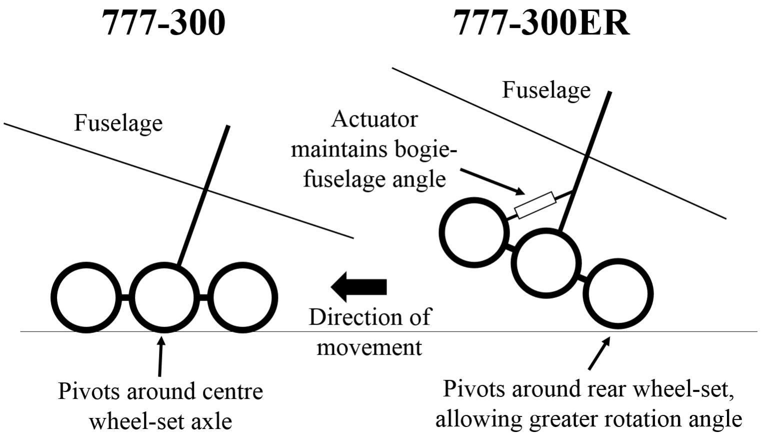


Figure 7: Boeing 777-300/-300ER main undercarriage at rotation during take-off.

shorter derivative of the 777-9 [39], which will be produced first and which itself will be a derivative of the 777-300ER.

The 777-9 and 777-8 are expected to have fuel-burn improvements of 20% and 13% per seat, respectively, as compared with the -300ER [91]. Changes to the 777-200 and -300 airframes, apart from stretching of the fuselage, are reported to be as follows:

- All-new General Electric GE9X engines. These will be the largest turbofan engines yet produced [92].
- Tailplane tip extensions of 1.52 m are to be added on each side [93].
- The vertical tail will be extended by 0.91 m [85].
- The wing will be new (but heavily based on the design of the 787 wing) and incorporate extensive use of composites. A major innovation on the 777X wing will be the introduction of folding wing tips. These will 'fold up' when on the ground to lower the wingspan from 71.75 m to 64.85 m [85], ensuring that the aircraft fits into existing airport taxiway and gates [39], [85]. The folding wing tips therefore allow a high wing aspect-ratio during flight, enhancing aerodynamic efficiency, while avoiding the need to upgrade existing airport infrastructure to accommodate the aircraft (as had to be done for the Airbus A380). The 777X will be the first commercial transport aircraft to feature such a mechanism and, as such, new certification rules had to be devised for it [94].
- New main landing gear wheels and tires will be incorporated [93].
- A new strut and nacelle are developed to accommodate the new engines [93].
- Aerodynamic advances will include hybrid laminar flow control on the vertical stabiliser and natural laminar flow nacelles [85].
- The wheelbase is made longer by 1.09 m and the engines centrelines have been moved outboard by 1.1 m [85]. Presumably, this was done to make room for longer undercarriage and the large new engines.
- According to Boeing [87], the cabin will be four inches wider than previous 777 models (by reducing the width of each side wall of the cabin by two inches), have larger windows and overhead luggage bins, lower cabin altitude, improved temperature control, cleaner air, and lower cabin noise (achieved by changing the nacelle design [85]). Like the airframe advances, many of these cabin innovations build on the experience gained with the 787 [87].

3.9 The 787 Family

In the late 1990s, Boeing was considering an all-new high-speed aircraft, dubbed the 'Sonic Cruiser' [95]. However, it later became clear that airlines preferred lower operating costs and higher efficiency to speed [95]. Therefore, in April 2004, Boeing launched a new type, then called the "7E7" [96] (E being for "efficiency, economics, environmental performance, exceptional comfort and convenience, and e-enabled systems." [97]). This was to be a twin-aisle aircraft that could transport around 200 to 250 passengers on nonstop, 'point-to-point' services, at speeds comparable with the 777 and 747 [97]. The 7E7 was to exploit substantial advances in materials (especially composites), airframe systems, and propulsion [95], but retain the conventional layout of previous Boeing twin-jets.

After well-publicised development woes, the 7E7, now referred to as the '787 Dreamliner', finally performed its maiden flight on the 15th of December 2009 [98]. The 787 sold extremely well from its launch onwards and, at the time of writing, over 1,400 have been ordered [41]. There are currently three production variants: the 787-8, 787-9, and 787-10. These are summarised in Table 11 and discussed in detail below.

The first Dreamliner was the 787-8. A stretched derivative of the 787-8, the -9, was part of the family plan from the beginning [99]. According to Boeing, as quoted by [99], the main differences from the 787-8 are as follows:

Table 11: Major variants of the Boeing 787 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
787-8	15/12/2009 [98]	22,990	13,620	444	Basic original variant.
787-9	17/9/2013	27,550	14,140	790	Stretched derivative of the 787-8 (plugs: 3.05 m fore, 3.05 m aft [99]), with longer range. Other than the fuselage, the other overall dimensions are the same as the 787-8. Significant internal changes to the airframe (see text).
787-10	31/3/2017	31,350	11,910	169	Stretched derivative of the 787-9 (plugs: 3.05 m fore, 2.43 m aft [99]). Some local airframe strengthening.

[a] Boeing [100].
[b] At time of writing (from Boeing [41]).

- The main undercarriage trucks are larger and the undercarriage features larger tires and brakes.
- The horizontal stabiliser design was "simplified from a three- to two-piece construction".
- A hybrid laminar-flow control system was added to the leading edge of the fin and horizontal stabiliser.
- The fuselage structure was strengthened locally, by increasing gauge thickness, whereas the frame design was updated to improve weight efficiency [99]. The manner in which the frames are constructed was also changed. In some cases, such as with the nose assembly, the gauge was actually made thinner. This was because it became clear that it was overdesigned originally.
- The wing has the same planform and area as the -8. However, to strengthen the wing for higher operating weights, it was locally optimised to save weight. The thickness of the wing skin has been increased and some of the fittings were made larger.

Unlike the more-often employed strategy of increasing the capacity at the expense of range, with the 787-9 both were increased significantly by increasing the MTOW [99]. This was made possible by substantial empty weight reduction (through applying experience acquired with the earlier -8) and the use of the novel hybrid laminar flow control system [99]. These improvements could perhaps be seen as disruptive architectural overhaul and had a negative impact on commonality with the -8. However, some of the advances obtained through the development of the -9 could be incorporated in the later -8 production aircraft [99].

The 787-10 was not actually originally conceived as part of the 787 family [101]. However, compared with the relatively large jump from the 787-8 to the 787-9, the -10 could be considered a 'simple' stretch. This is because it was certified with the same MTOW as the -9 [98], which reduced the extent to which the airframe had to be strengthened [102]. About 95% of the -9 part numbers are reused on the -10, enabling exceptionally high commonality across the two variants [102]. The ease at which the -10 was devised could perhaps also be attributed to the architectural overhaul of the -8 to the -9.

4 Case Studies in Evolvability: McDonnell Douglas Aircraft

McDonnell Douglas (and especially the preceding Douglas Aircraft Company) produced many famous and celebrated transport aircraft. The company experienced increasing financial problems and merged with Boeing in the 1990s.

Table 12: Major variants of the Douglas DC-8 family.

Variant	First flight [43]	Payload [kg]	Range [km]	No. sold[a]	Description
DC-8-10	30/5/1958	16,458 [14, p. 533]	7,108 [14, p. 533]	26	Basic original version.
DC-8-20	29/11/1958	16,458 [14, p. 533]	7,604 [14, p. 533]	36	Variant of -10 with more powerful engines.
DC-8-30	21/2/1959	16,458 [14, p. 533]	8,258 [14, p. 533]	57	First Intercontinental version. Increased fuel capacity and operating weights, along with changes to the wing from Srs 32 onwards (see text).
DC-8-40	23/7/1959			32	Similar to -30 but fitted with Rolls-Royce engines.
DC-8-50	20/12/1960			143 (incl. 55)	First DC-8 variant to be fitted with turbofan engines.
DC-8-55	29/10/1962	17,574 [39]	8,519 [39]	Incl. in -50	Similar to Srs 50, but with increased passenger capacity.
DC-8-61	14/3/1967	24,083 [39]	5,926 [39]	88	First stretched variant. Fuselage stretched by 11.18 m [43, p. 117]. Some local strengthening of the airframe.
DC-8-62	29/8/1966	17,574 [39]	9,612 [39]	67	Extra-long-range version. Stretch of 2.03 m of Srs 55 fuselage. New wingtips, along with other airframe changes.
DC-8-63	10/4/1967	24,083 [39]	7,408 [39]	107	Same as the Srs 61, but incorporating the advances made with the Srs 62.

[a] Boeing [41]. Includes cargo variants; excludes military models.

4.1 The DC-8

In June 1955, almost a year after the Boeing 367-80 first flew, Douglas decided to also pursue a jet transport aircraft [43, p. 116]. The aircraft would be known as the DC-8 and the design that emerged looked very similar to the 367-80 and the subsequent 707 [43, p. 116]. It first flew on the 30th of May 1958, powered by Pratt & Whitney JT3C engines [43, p. 116].

There were several derivatives of the DC-8 (See Table 12). These were referred to by McDonnell Douglas as 'Series' and designated by 'DC-8', followed by a dash (–) or the abbreviation 'Srs', followed by the series number. Series 10 to 50 employed the same fuselage [43, p. 117] and had identical dimensions for all other components (apart from the wings, which received small tip extensions). From Srs 60, stretched versions started to appear [43, p. 117].

Srs 10 (DC-8-10) was the original 'domestic' model and entered service in September 1959 [43, p. 117]. The DC-8-20 operated at lower weights than the Srs 10, but used the more powerful engines to provide improved field performance [43, p. 116].

Developed for intercontinental services [14, p. 516], the DC-8-30 featured longer ranges than the -10 and -20 and was powered by JT4A engines [43, p. 116]. The fuel capacity was increased over that of the Srs 20, increasing the range [14, p. 516]. Compared with the Srs 10 and 20, the Srs 30 had a higher MTOW, which meant that it required longer runways for take-off [14, p. 517]. Therefore, although the subseries Srs 31 still had the same wing configuration as the DC-8-21, leading-edge droop flaps were added to the wings of the -32 and -33 [14, p. 517]. In addition, the leading edge on these subvariants was modified (recontoured) to increase the wing chord by 4% [43, p. 116]. The Srs 40 was almost identical to the Srs 30 but was fitted with Rolls-Royce Conway engines [43, p. 16]].

The DC-8-50 was the first to sport new turbofan engines, which were housed in new nacelles [14,

p. 518]. For the subseries, Srs 55, the aft bulkhead was moved rearwards, which made room for an increased capacity of up to 189 passengers [14, p. 519].

According to Francillon [14, p. 520], when the DC-8 was designed, a substantial margin for growth (excess, promoting scalability) was provided (unlike with the 707). This was done by incorporating long undercarriage struts and a pronounced upward sweep of the rear fuselage, which would ensure that the fuselage could be easily stretched while leaving enough room to still properly rotate at take-off [p. 521]. It is therefore surprising that it was only with the Series 60 that these margins were finally exploited. Three new versions (subseries of the Srs 60) were launched in April 1965 [43, p. 117]. The Srs 61 and Srs 63 featured the same fuselage stretch of 11.18 m, whereas the Srs 62 had a shorter increase in length of 2.03 m [43, p. 117].

The Srs 61 had the same wing, tail surfaces, engines, and fuel capacity as the -55, although some local strengthening of the structure was applied and the flaps were improved [14, p. 521]. The -61 could therefore be considered a 'simple stretch'. The -61 had the same MTOW as the Srs 55 and, because it had a much higher passenger capacity than that model, range diminished.

The -62 was developed for extra-long ranges with the Srs 55 as baseline [14, p. 522]. Aerodynamic improvements were also implemented, which included a wingspan increase of 1.83 m with more efficient wingtips [43, p. 117]. The Srs 62 also featured higher fuel capacity [14, p. 522]. The -63 combined the longer fuselage of the -61 with the wing and powerplant advances of the -62 [14, p. 524], and was aimed at the transatlantic market.

From 1979, a company called Cammacorp converted existing DC-8-60 aircraft to be powered by the more modern, quiet, and efficient CFM56 turbofan engines [43, p. 117]. These received the Srs 71, 72, and 73 designations and, as they were retrofits, they are not covered in further detail here.

4.2 The DC-9 and descendant families

In the early fifties, the Douglas company performed studies for a small jetliner with medium range to complement the DC-8, which was just launched [43, p. 144]. This aircraft was originally planned to be a reduced scale version of the DC-8 with four engines, but this was later abandoned [14]. Instead, a new design was proposed, featuring a T-tail and rear fuselage-mounted turbofan engines [14].

The DC-9 was launched on the 8th of April 1963 [43, p. 114]. Little is common with the DC-8 and the DC-9 can be considered a clean-sheet design [43, p. 114]. However, by observing the nose and cockpit geometry one can notice that it is based heavily on that of the DC-8.

Like the DC-8 before it, the DC-9 was planned for significant growth from the start of the programme [14]. In fact, it seemed more amenable to growth than the British Aircraft Corporation (BAC) 1-11, which was limited by its engines, of which the thrust could not be increased much (i.e. lack of scalability) [14]. This enabled the DC-9 to be more competitive early in its career [14]. It eventually evolved into the MD-80, MD-90, and later the Boeing 717 families. In the next subsection, the original DC-9 variants are discussed, followed by the MD-80, the MD-90, and the Boeing 717.

4.2.1 The DC-9

All DC-9 versions were powered by variants of the Pratt & Whitney JT8D engine. With 831 built (excluding military versions and the later MD-80), the DC-9 was the most successful of Douglas Commercial jet aircraft [14, p. 535]. Salient information regarding the DC-9 variants is summarised in Table 13. The first version was the Series 10. It took off on its maiden flight on 25 February 1965 [14, p. 537].

The series 20 featured a 1.22 m longer wingspan than the Series 10. This modification was originally applied to the Series 30 (which preceded the Series 20) by means of adding extensions at the wingtips. Also, like the Series 30, the Series 20 employed full-span leading edge slats for improved field performance and featured more powerful engines [14, p. 538]. The fuselage length was the same as that of the -10 [43, p. 144].

The Series 30 followed the Series 10 into production (before the Series 20) and featured a 4.57 m stretch of the -10 fuselage [14, p. 539]. This was a relatively straightforward modification, because the MTOW of the Series 10 was at first limited to 80,000 lb (which was the FAA maximum restriction at

Table 13: Major variants of the McDonnell Douglas DC-9 family.

Variant	First flight [103]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
DC-9-10	25/2/1965	8,200	2,434	137	Original version of the DC-9.
DC-9-20	18/9/1968	8,200	2,689	10	More powerful engines and changes to slats [14, p. 538]. Same fuselage length as Series 10 [43, p. 144].
DC-9-30	1/8/1966	10,750	2,391	621	4.57 m stretch of the -10 fuselage [14, p. 539].
DC-9-40	28/11/1967	11,692	2,019	71	1.88 m stretch of the -30 fuselage [14, p. 541].
DC-9-50	17/12/1974	12,289	2,534	96	2.44 m stretch of the -40 fuselage, same wing dimensions as on Srs 30 and 40, but more powerful engines and increased MTOW [14, p. 542].

[a] Boeing [39].

[b] Boeing [41]. Includes cargo variants; excludes military models.

the time for two-man crews) and its engines were much derated in terms of thrust [14, p. 539]. The aforementioned changes to the Series 10 wing (see the preceding paragraph) were performed to ensure that the field performance of the Series 30 remained acceptable.

The series 40 was a further stretch. The subsequent increase in payload capacity was made at the expense of range and runway length requirement [14, p. 541]. Another fuselage stretch was performed to create the Series 50, which was announced in 1973.

4.2.2 The MD-80

From 1975, Douglas studied how the DC-9 could be evolved further by taking advantage of the emerging turbofan JT8D-200 series of engines [43, p. 146]. As a result of these, the 'DC-9 Series 80' was launched in October 1977. However, it was soon renamed as the 'MD-80' [43, p. 146] to reflect the McDonnell and Douglas merger. It had a 4.34 m longer fuselage than the DC-9-50.

However, the wing was changed substantially (see Figure 8). To increase the span, a centre-section plug was inserted and parallel-chord span extensions of 0.61 m were added at the wingtips [104]. These changes allowed an increase in weight while keeping field-length performance acceptable.

Information on the different variants of the MD-80 are summarised in Table 14. At first, the MD-80 consisted of three subvariants, known as the MD-81, MD-82, and MD-83. These had the same overall dimensions, but differed in engine power, fuel capacity, and operating weights [43, p. 146]. They were followed by the MD-87, which was announced in 1985 [43, p. 146]. The MD-87 featured a shorter fuselage and the tailfin had to be extended by 25.4 cm above the horizontal stabiliser [43, p. 146]. On later MD-87 models, a new low-drag tailcone was adopted [104], which became standard on subsequent variants.

In 1986, another member of the MD-80 family was launched. This variant was called the MD-88 and was similar to the MD-82 but featured a number of system refinements [43, p. 146].

4.2.3 The MD-90

The MD-90 represented the next generation of the family, which again attempted to exploit advances in engine technology [105]. The project was not successful and only 116 MD-90s (all variants of the MD-90-30) were produced [41]. The engines were, once again, heavier and so the fuselage had to be stretched a further 1.37 m to balance this increased weight at the back [105]. An extended range (ER) version was built, dubbed the MD90-30ER, which featured increased fuel capacity and higher weights.

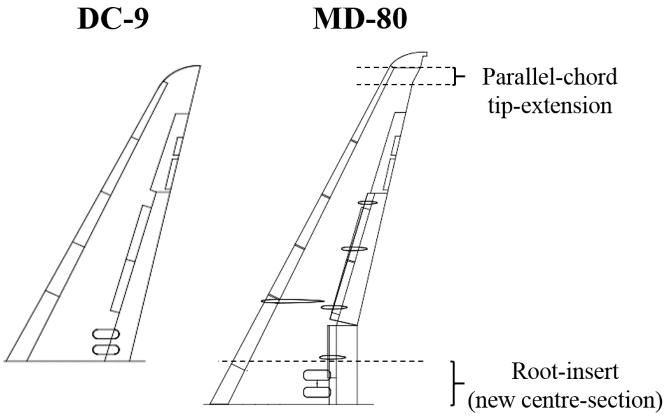


Figure 8: McDonnell Douglas DC-9 and MD-80 wing comparison (from Boeing CAD drawings [42] – used under license agreement with the Boeing Company).

Table 14: Major variants of the McDonnell Douglas MD-80 family.

Variant	First flight [104]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
MD-81	18/10/1979	12,820	3,334	132	Basic version.
MD-82	8/1/1981	12,820	3,889	569	Higher thrust engines for hot and high conditions and increased payload/range [104].
MD-83	1712/1984	12,820	4,824	265	Extended range version. Two additional fuel tanks in cargo compartment. Higher thrust engines [104].
MD-87	4/12/1986	11,984	5,371	75	5 m shorter fuselage length than MD-81/-82/-83 and taller tailfin [43, p. 146].
MD-88	15/8/1987	12,820	3,889	150	Similar to MD-82, but with more advanced systems and increased use of composites [104].

[a] Boeing [39].

[b] Boeing [41].

Table 15: Major variants of the McDonnell Douglas DC-10 family.

Variant	First flight [108]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
DC-10-10/15	29/8/1970	26,000	6,482	138	Basic original version.
DC-10-30	21/6/1972	26,000	9,842	206	Derivative of the DC-10-10, with increased fuel capacity. The wingspan was increased slightly and a centreline gear leg was added to the main undercarriage.
DC-10-40	28/2/1972	26,000	9,260	42	Similar to the -30 but employed Pratt & Whitney engines.

[a] Boeing [39].

[b] Boeing [41]. Includes cargo variants; excludes military models.

4.2.4 The MD-95/Boeing 717

The MD-95, launched in 1995, was the next step in the development and was optimised for short flights of less than 400 nm (740 km) [106]. It first flew on the 2nd of September 1998 [106] and was renamed the 'Boeing 717' after Boeing took over McDonnell Douglas in 1997 [107]. The fuselage was 1.45 m longer than the DC-9-30 and featured almost the same wing as the heaviest DC9s, but which was aligned at a higher incidence angle [107]. Only 155 717s were produced [41].

4.3 The DC-10 and MD-11

The DC-10 was developed by McDonnell Douglas in response to a requirement from American Airlines for an aircraft that could fly long-haul services from short runways [108]. It was a single deck widebody that employed a distinctive three-engine layout. The DC-10 was manufactured in three basic variants: the -10, -30, and -40 (see Table 15). All the variants had the same fuselage dimensions [39].

The Series 10 was the original, 'domestic' variant [108]. After it was introduced. The Series 30 was the intercontinental version [108] and had a higher fuel capacity than the Srs 10. It was heavier and required an extra landing gear leg on the centreline of the fuselage (as stated before, Boeing learned this lesson and subsequently designed the 777 to be more scalable by incorporating six-wheel bogies). An extended-range version of the Srs 30, the DC-10-30ER, was also introduced and featured an extra fuel tank in the rear cargo compartment [108]. The DC-10-40 was similar to the -30ER but employed Pratt & Whitney engines [108].

The MD-11 was a major upgrade of the DC-10. It was launched on the 30th of December 1986 and first took the skies on the 10th of January 1990 [109]. The DC-10 fuselage was stretched by 5.67 m using two plugs [110]. The profiles of the wing trailing edge and tips were modified and Whitcomb-style winglets were added [111]. The tail-cone was also recontoured to reduce drag [110]. The horizontal stabiliser was made significantly smaller and featured a new advanced cambered aerofoil, revised trailing-edge camber, less sweep, and a trim fuel tank [108]. More advanced propulsion was employed. Despite these changes, much of the DC-10 tooling could be reused on the MD-11 [110].

Further stretches were planned by McDonnell Douglas [112, p. 68]. Unfortunately, with 200 sold [41], the MD-11 was not that successful and the company experienced increasing financial problems. McDonnell Douglas merged with Boeing in 1997 and these projects were subsequently abandoned.

5 Case Studies in Evolvability: Airbus Aircraft

The formation of Airbus reflected a rising level of European collaboration and the merging of many aerospace companies during the 1960s and 1970s. Airbus has since grown into an enormously successful enterprise, producing some of the most competitive and innovative airliners in the world.

5.1 The A300

Airbus's first endeavour, the A300, emerged in the late 60s to early 70s as a 252-passenger twin-engined jet transport, with a range of about 1,200 nm (2,224 km). This aeroplane was officially designated the 'A300B1' and performed its maiden flight on the 28th of October 1972 [43, p. 52]. Despite scepticism from the industry, the A300 sold well, with a total of 561 [113] (of all variants) ordered before production ended in 2007 [114].

The A300 was designed with possible future growth in payload and range capacity very much in mind. According to Gunston [115, p. 37], there was ample room in the main wing box for more fuel for longer ranges and the range was eventually increased to up to 4,400 nm (8,154 km) for the -600 model, without "any change in the external size of the wing". The geometry of the undercarriage would also not have to change if the fuselage were to be stretched to increase passenger capacity by up to 25% [p. 37]. The gross weight could be increased significantly with only minor strengthening of the airframe structure (from 137 tonnes for the B2 to 170.5 tonnes for the -600R) [p. 46]. These are powerful examples of excess.

Gunston also states that, long before the A300 even flew for the first time, derivatives were already being studied [p. 85]. These initial designs received the designations of A300B1 to A300B9. The B1 was the first aircraft to fly; the B3 was never produced, and the B2 and B4 were improvements of the B1 (as discussed below). Note that the B1, B2, and B4 (but not the later, improved A300-600) are collectively referred to in this text as the 'A300B'. An additional variant, the B10, was studied in 1973 and eventually became the Airbus A310 (see Section 5.2). The B9 and a later-added B11 were eventually developed into the Airbus A330 and A340 respectively (covered in Section 5.4). The other derivative designs were never produced.

The main A300 variants are listed in Table 16, along with salient information. The A300B2 superseded the A300B1 and flew for the first time on the 28th of June 1973. Its fuselage was 2.65 m longer than the B1 prototypes [43, p. 52].

The A300B4 was the longer-range variant. It featured an added centre fuel tank and, for the later A300B4-200, additional fuel capacity was made available by adding fuel tanks in the rear cargo hold [43, p. 53]. A much-improved version of the B4, the A300-600 was launched in 1980 [43, p. 53]. It featured the rear fuselage geometry of the Airbus A310 (discussed in the next subsection) with the rear bulkhead moved aft, which enabled two more rows of seats to be added [115, p. 83]. The wing was almost the same as the A300B, but simpler, single-slotted flaps were adopted [115, p. 83].

Other improvements included more advanced engines, an increase in the use of composites, and simpler systems, which decreased structural weight [43, p. 53]. According to Gunston [115, p. 83], a single frame was added to increase the length of the fuselage by 520 mm. Furthermore, the smaller horizontal stabiliser of the A310 was adopted for the -600 [p. 83]. Also, to further incorporate advances made with the development of the A310, the rudder material was changed to composites and the outboard low-speed ailerons were removed [p. 83]. These modifications reduced drag by about 4%, whereas the landing lift-coefficient was increased by 8% [p. 83].

The next significant upgrade was referred to as the A300-600R. Small 'wingtip fences', which reduce lift-induced drag, were added, along with a trimming fuel tank in the horizontal stabiliser [43, p. 53].

5.2 The A310

Gunston [115] states that "Few builders of aircraft have ever had a better basis for derivative aircraft than the A300, and right from the start AI [Airbus Industrie] recognised that it had to ring the changes as far as its tight funding would permit". The first major derivative was the A300B10 (later called the A310).

The A310 was developed based on a requirement from some airlines for a smaller version of the A300B [115]. The A310 fuselage was 13 fuselage frames shorter than that of the A300B. The aft fuselage section was also 'reprofiled' and the rear pressure bulkhead moved further back to allow for more rows of seats to be added [43, 118, 115]. As already stated, the rear fuselage changes discussed here were later adopted for the Airbus A300-600. Apart from these modifications, the fuselage received

Table 16: Major variants of the Airbus A300.

Variant	First flight [114]	Payload [kg][a]	Range [km][a]	Description
A300B1	28/8/1972			Original version.
A300B2	28/6/1973 [43, p. 52]	24,270	2,778	2.65 m longer fuselage than the B1. B2K featured Krueger flaps.
A300B4	26/12/1974	24,270	5,050	Longer range variant of B2. Strengthened airframe and additional fuel capacity.
A300-600	8/7/1983	25,775	6,600	Advanced version of the B4. Featured airframe changes developed for the A310.
A300-600R	9/12/1987	25,270 [116]	7,408 [116]	Extended range version of A300-600 with wingtip fences and trim fuel tank added in the horizontal stabiliser [114].

[a] Airbus [117], except where indicated otherwise.

only minor further refinements [115]. The A310 was powered by several versions of the Pratt & Whitney JT9D and General Electric CF6 engines [43].

During the initial development of the A310, there was much disagreement from within the manufacturer on whether to incur the expenses of designing a new wing to better suit the envisioned shorter fuselage [115]. Only after the insistence of Lufthansa was it decided that a re-design was necessary [118]. The wing was, from an aerodynamics point of view, "completely new", but remained structurally very similar to the wing of the A300B [43, p. 54]. Although the third inboard spar of the A300 wing was removed, the rib design and spacing remained little changed, apart from a reduction in chord to increase the wing's aspect ratio [115, p. 100]. This had the additional effect of increasing the thickness-to-chord ratio. This is the only example found of a reduction in chord length.

According to Gunston [115, p. 100], the biggest structural modification was that the wing skins were produced in larger sections, which reduced mass at the skin joints. The outboard aileron was eliminated, as it proved to be redundant and the A300B's flaps were replaced by new, simpler ones [p. 103]. The A310's leading-edge slats featured larger chords and radii, which improved field-performance [118, p. 26]. Also, extensive use of newer lightweight alloys and composite materials was made [115, p. 104]. These changes to the geometry and components of the wing necessitated a redesign of the wing centre-section [118, p. 26].

The vertical tail of early A310s remained common with the A300B, whereas the horizontal tail was a scaled-down version of the A300's [118, p. 27]. The main undercarriage was almost totally re-designed to minimise weight [115, p. 104], but the nose gear remained similar to that of the A300B.

The maiden flight of the A310 was on the 3rd of April 1983 [43, p. 54]. It was originally offered in two variants (see Table 17), the -100 and -200, but the -100 was later abandoned [43, p. 54]. The later A310-300 design focussed on increasing the range of the basic variant (the -200). The increase in range from the basic A310-200 was achieved with almost no external changes in geometry. A total of 255 [113] A310s (of all variants) were sold.

5.3 The A320 Family

Alongside the design effort of the Airbus A300, many European aerospace companies were separately considering the development of a 150-seat, single-aisle airliner family [120]. Such a family was to succeed the British Aircraft Corporation One-Eleven and the Sud Aviation Caravelle, and to compete with the highly successful American Boeing 737 and McDonnell-Douglas DC-9 [120]. Many of these

Table 17: Major variants of the Airbus A310.

Variant	First flight	Payload [kg][a]	Range [km][a]	Description
A310-200	3/4/1982 [119]	21,835	6,650	Basic version. Major derivative of the Airbus A300B.
A310-300	8/7/1985 [43, p. 54]	22,468	9,538	Extended-range version. Added horizontal stabiliser trim fuel tank (later also used on the A300-600R) and optional underfloor fuel tanks [115, p. 109]. Small wingtip fences added (also implemented on later A310-200 models and used on the A300-600R [43, p. 54]). The -300's fin was made from carbon-fibre [115, p. 113].

[a] Airbus [117].

companies eventually came together to form the Joint-European Transport (JET) programme, which would study a CFM56-powered three-member aircraft family [120]. JET was later incorporated into the Airbus Consortium, in which it became known as the SA (Single-Aisle) programme. The programme encompassed three members – SA1, SA2, and SA3, seating between 125 and 188 passengers [120]. The focus was initially on the 150-seat SA2, which would become the A320, whereas SA1 became the A319 and SA3 became the A321 [120]. The original efforts of the European companies did not go to waste and some elements of the new design originated from the earlier studies. One example is the wing design, which evolved from studies performed in Britain for the BAC Three-Eleven, which was never produced [115, p. 169].

The A320 was officially launched on the 23rd of March 1984 [121] and the family has since become phenomenally successful. Over 14,000 A320-family aircraft have been ordered by December 2018 [122, 123, 121, 124]. Some major innovations that came with the introduction of this family included the first use in civil transport aircraft of a digital fly-by-wire system, sidestick controllers, new cockpit displays, and a gust-alleviation system. The members of this illustrious family now encompass the A318, A319, A320, and A321, as well as 'new engine options' for these (see Table 18). All members share the same basic wing and tail geometry, apart from a small increase in wing area for the A321 and a higher tail for the A318.

5.3.1 Original A320 family members

The first flight of the A320 was on February 22, 1987 [121]. There were two versions of the original A320 – the -100 and -200, with the -200 becoming more popular[121]. From 2012, the option of having 'sharklets' (large winglets) was available [121]. These were also available as retrofits from 2013 on all A320 family members [121].

The stretched A321 was launched on the 24th of November 1989 [124]. More powerful engines were fitted and the airframe and the undercarriage were strengthen-ed [124]. The flaps were changed from being single- to double-slotted [124]. The flaps were also larger, such that it increased the chord of the wing slightly [127, p. 72] (see Figure 9). This was most likely done to maintain acceptable low-speed and field performance [127, p. 72]. The original A321 versions were the A321-100 and an increased MTOW, longer range/higher capacity A321-200 (launched in 1995) [124].

The next variant, the A319, featured a shortened fuselage and was launched on 10 June 1993 [123]. It was followed by the A318, the smallest of the A320 family, which was launched on the 26th of April 1999 [122]. The A318 features a shortened A319 fuselage and, to ensure that directional stability remained acceptable, the vertical tail had to be made taller by means of a tip extension [122].

Table 18: Major variants of the Airbus A320 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
A318	15/1/2002 [122]	10,165	5,750	80	Shorter derivative of the A319 (0.79 m fuselage plug removed in front of wing, 1.6 m behind wing [122]). Taller tailfin.
A319 ceo	29/8/1995 [123]	11,780	7,100	1,486	Shorter derivative of the A320 (1.6 m fuselage plug removed forward of wing and 2.13 m removed aft). De-rated engines. One over-wing emergency exit pair removed.
A319 neo	31/3/2017 [123]	11,780	8,000	55	New-engine option of the A319. Same changes as for A320neo.
A320-100	22/2/1987 [121]	14,250		incl. in -200	Original A320 family aircraft. Superseded by the A320-200.
A320-200	1987/1988 [121]	14,250	5,340	4,770[c]	More advanced version of the A320-100. Addition of large centre-section fuel tank and wingtip fences [121].
A320 neo	25/9/2014 [121]	14,250	6,750	4,191	New-engine option of the A320-200 (see text for airframe modifications).
A321-100	11/3/1993 [124]	17,575	4,432	incl. in -200	Stretched derivative of the A320 (plugs: 4.27 m fore, 2.67 m aft) [124]. Each plug has two doors. Features more powerful engines, strengthened undercarriage, and revised trailing-edge flaps.
A321-200	12/12/1996 [124]	17,575	5,580	1,799[d]	Higher MTOW variant of A320-100. Features higher thrust engines, structural strengthening, and extra fuel capacity in additional centre fuel tanks [124].
A321 neo	9/2/2016 [124]	17,575	6,150	2,280[e]	New-engine option of the A321-200. Same changes as for A320neo.
A321LR	31/1/2018 [125]	19,570 [126]	7,408 [126]	incl. in neo	Long-range version of the A321neo. MTOW increased and a third additional supplementary fuel tank added [124]. Undercarriage and wing were reinforced [124].

[a] Airbus [117], except where indicated otherwise.

[b] At time of writing (from Airbus [113]).

[c] Includes -100 and all ceo versions.

[d] Includes -100 and all ceo versions.

[e] Includes LR.

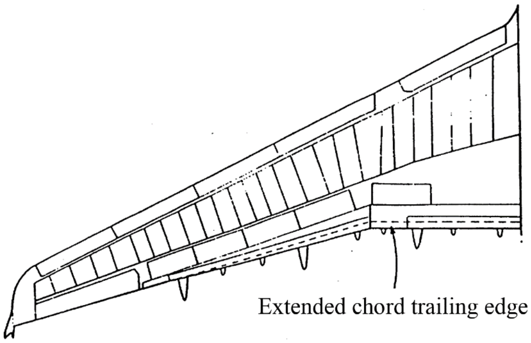


Figure 9: Planform view of the A321 wing showing the chord extension of the A320 baseline wing [127, p. 73]. Image used with permission of NASA.

5.3.2 New Engine Option

New engine option (neo) variants of the A319, A320, and A321 were launched in December 2010 [121]. The engine options were for the CFM International LEAP-X or Pratt & Whitney PW1127G [121]. Apart from the new engines, airframe modifications include new pylons, as well as strengthened undercarriage and outer wings. All A320 family neos come with 'Sharklet' winglets [121]. A long-range version of the A321neo, the A321LR, was launched on the 13th of January 2015 [124] and certified on 2 October 2018 [128]. The latest neo model, the A319neo, achieved certification on 21 December 2018 [129].

5.4 The A330 and A340 families

By the late 1970s, the B9, B10, and B11 (later called TA9, TA10, and TA11 for 'twin-aisle') concepts were considered by Airbus to be the most promising derivative options of the A300B [115]. As mentioned before, TA10 eventually became the A310. TA11 was intended to replace ageing Boeing 707s and McDonnel Douglas DC-8s, whereas the TA9 was aimed at high-capacity medium-range routes. TA9 and TA11 later became known as the A330 and A340, respectively [115].

The twin-jet A330 and four-engined A340 were developed in parallel, as customers could not agree whether they preferred two or four engines [130] and the cost-saving benefits of significant commonality was recognised. Both designs were to employ almost identical wings, which featured large canted winglets [131]. The wing changed with later variants, and some of the major modifications are shown in Figure 10. The structural layout of the wing design was similar to the earlier A300, whereas, aerodynamically, the wing was "a direct relation to the A310" [132, p. 51]. The A330 was originally intended for short-to-medium range services, whereas the A340 was optimised for long-haul operations [132, p. 51]. The A340 was therefore initially much heavier than the A330 and required an extra main undercarriage bogey [132, p. 51]. The fuselage cross-section of the A330 and A340 family members is the same as that of the A300 and A310. The fuselage construction and geometry are generally also the same as for the A300 and A310, except for the centre-section, where the new wing is attached [131]. Furthermore, the tail unit is the same as on the A300-600 and A310 (except for the A330-200, A340-500, and A340-600, which have larger tail surfaces) [131].

The Airbus A330 proved to be significantly more successful than the A340. Over 1,700 A330s (in all variants) have been ordered at the time of writing [131] compared with a total of only 377 for the A340 (production ended in 2011) [134]. There are several reasons for this – many relating to the four engine configuration. As turbofans became progressively more reliable, twin-engined jets were increasingly permitted to operate on long transoceanic routes, with large distances from the nearest land to divert to in the case of engine failure (i.e. under 'Extended range Twin-engined Operations' [ETOPS] regulations [135]). This opened up routes, formerly only permitting three- or four-engined operations, to twinjets, such as the A330 and Boeing 777. Because two-engined jet aircraft generally

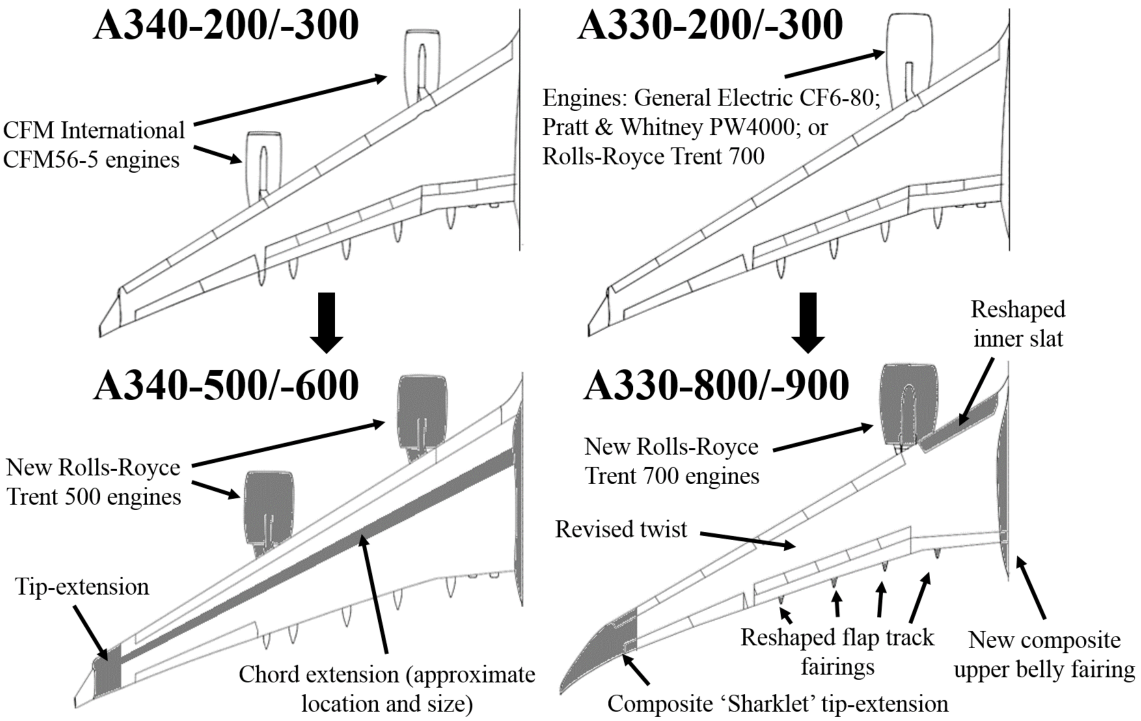


Figure 10: A330/A340 wing evolution (planform geometries from Airbus CAD drawings [133] – used with permission of Airbus).

Table 19: Major variants of the Airbus A330 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
A330-200	13/8/1997 [131]	23,465	12,565	707[c]	Shorter fuselage length, longer-range variant of A330-300.The centre fuel tank of the A340 was adopted, necessitating strengthening of the wing [132, p. 94]. The tip of the tailfin was extended by 1.04 m [132, p. 94] and the chord was increased. The fin was later shortened again by 50 cm [117, p.3 and p.5].
A330-300	2/11/1992 [131]	28,500	11,000	789[d]	First A330 model.
A330 high gross-weight	12 Jan 2015 [131]	28,500 (-300) [131]	11,927 (-300) [131]	incl. in -200 and -300	High gross-weight (MTOW of up to 242 tonnes) versions of the A330-200 and -300. Aerodynamic refinements, including reshaped inboard slats and shortened flap rack fairings, more advanced engines fitted [131].
A330 Regional	Launched Sep 2013 [131]	38,000 [138]	5,556 [138]	incl. in -300	Lower weight variant of the A330-300.
A330-800	N.A.	24,415 [139]	13,900 [139]	8	New engine option, based on the A330-200 [130]. Same changes as applied on A330-900.
A330-900	19/10/2017 [131]	27,265 [140]	12,130 [140]	230	New engine option derivative of the A330-300 [130]. See text for modifications.

[a] Airbus [117], except where indicated otherwise.
[b] At time of writing (from Airbus [113]). Includes cargo variants; excludes military models.
[c] Includes High Gross Weight and cargo variants.
[d] Includes High Gross Weight and Regional variants.

have lower operating costs than their four-engined counterparts of similar range and payload [136], airlines were increasingly inclined to favour the 777 and A330 over the A340 [137]. This became even more prevalent when longer-range, higher gross-weight variants of the A330 became available.

5.4.1 The A330

The major A330 variants are summarised in Table 19. The A330-300 was the first version. It took off on its maiden flight on the 2nd of November 1992, which was after that of both the A340-200 and A340-300 [131], [134]. Airbus launched a shorter fuselage variant, the A330-200, in November 1995 [131]. This variant had longer range, but at a reduced payload capacity [131].

An optional increase in MTOW of up to 242 tonnes became available for both the -200 and -300 in November 2012 [131]. With this modification, the centre fuel tank of the A330-200 also became available on the -300 [131] (mimicry). A regional version was announced in September 2013, which is a lower weight derivative of the A330-300 [131].

The re-engined A330 design, the 'A330neo' ('new engine option'), was launched in 2014 [130].The neo features more efficient Rolls-Royce Trent 7000 engines [130] and Airbus claims a 14% fuel reduction per seat [141]. The larger engines are accommodated by new pylons and new composite nacelles with noise-reduction features [130]. They are mounted higher above the ground to ensure that the same amount of ground clearance as with the earlier A330 is maintained [142].

The first neo to fly was the A330-900. It has the same fuselage dimensions as the A330-300, but features several aerodynamic improvements [130]. The winglets are replaced by composite blended 'sharklets' [131], which increase the span by 3.7 m to 64 m [131]. The twist of the wing has been

Table 20: Major variants of the Airbus A340 family.

Variant	First flight [134]	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
A340-200	1/4/1992	27,624	14,100	28	Shorter fuselage length, longer range variant of A340-300.
A340-300	25/10/1991	31,600	13,240	218	Original basic variant. Preceded the A330.
A340-500	11/2/2002	29,735 [38]	15,742 [38]	34	Ultra-long-range variant of the A340-600.
A340-600	23/4/2001	36,100 [38]	13,890 [38]	97	Stretched derivative of the A340-300 (see text for modifications).

[a] Airbus [117], except where indicated otherwise.

[b] Airbus [113].

revised and the upper belly fairing has been replaced with a new composite fairing [131]. The flap track fairings have been reshaped [131]. Furthermore, extensive strengthening of the wing is said to have been required [142]. Despite these changes, 95% spares commonality with previous versions of the A330 is maintained [141]. The -900 received certification on 26 September 2018 [143]. The smaller A330-800 model is derived from the airframe of the A330-200 [130].

5.4.2 The A340

The A340 (Table 20) is the four-engined member of the A330/A340 family. Versions of the CFM56 (used on Boeing 737s and A320s) were adopted for the early A340s (the -200 and -300 models) [130]. The first A340 (an A340-300) flew in October 1991 [130]. The A340-200 is the longer-range version with a shorter fuselage. Later -200 models received additional fuel tanks in the rear cargo hold, with a strengthened airframe, and more powerful engines [134].

Eyeing the 747-replacement market [132, p. 106], Airbus launched the A340-500 and -600 variants in 1997 [134]. Both were powered by four Rolls Royce Trent 500 engines [134]. The -600 was a derivative of the A340-300, featuring a 20-frame stretched fuselage [134]. Changes to the empennage included a scaled-up horizontal stabiliser, an increase in chord of the vertical stabiliser, along with a tip extension of 0.5 m [134]. This was similar to the changes made to the A330-300 fin to create the A330-200 fin. The main undercarriage had to be modified to include an extra set of wheels on the centre leg [134].

The most significant changes applied, however, were to the wing. A wedge-shaped (tapered) insert was built into the wing box to extend the chord of the wing (by 1.6 m where the wing meets the fuselage) [132, p. 108]. The fuselage also had to be extended at this location by a 1.6 m plug [134]. Furthermore, a tip-extension was introduced, which increased the overall wingspan to 63.4 m [134]. The tapered insert increased the sweep of the wing from 30° to 31.5° [132, p. 108]. The changes to the wing resulted in an 20% increase in wing area and 38% increase in fuel capacity [132, p. 108]. Increasing the size of the wing in this manner enabled many of the leading and trailing edge high-lift devices and components to remain common with the earlier A340s [132, p. 108]. This commonality probably came with a penalty though, rendering the wing less aerodynamically efficient than a new, optimised design would have been. This may have further increased the efficiency advantage that the 777 had over the A340.

The A340-500 featured the same changes than the -600 but was stretched 14 frames less (receiving a 0.53 m plug in front of the wing and a 1.07 m plug aft of it, plus the 1.6 m where the wing chord is increased). It had capacity for additional fuel in the rear centre tank [134].

Table 21: Major variants of the Airbus A350 family.

Variant	First flight	Payload [kg][a]	Range [km][a]	No. sold[b]	Description
A350-800	N.A.				Shorter variant of the -900. Not developed further yet.
A350-900	14/6/2013 [145]	30,875	15,000	724	Basic version.
A350-1000	24/11/2016 [145]	34,770	14,750	170	Stretched derivative of the -900 (see text for modifications).

[a] At time of writing (from Airbus [117]).

[b] Airbus [113].

5.5 The A350 Family

Recognising the need to compete with the Boeing 787, Airbus originally proposed a design that was essentially an A330, but with an improved wing, engines, and horizontal stabiliser, more extensive use of composites, and new production methods [144]. However, after negative feedback from the airlines, Airbus launched a clean-sheet design, called the A350XWB (eXtra Wide Body), on the 1st of December 2006 [145].

As with the 787, a conventional twin-engined layout was adopted and extensive use was made of composites in the A350 design [145]. Much of the experience gained with the A380 was exploited during development. For example, the nose [146], avionics [147], and hydraulic system [145] designs were all derived from those of the A380. The powerplant was developed by Rolls-Royce and is called the 'Trent XWB' [145]. It was decided that the fuselage would be wider than the A330/A340 and (significantly) the 787 [148] (hence the XWB suffix), allowing for greater passenger comfort.

Thus far, the A350 has sold well and 890 have already been ordered at the time of writing [145]. Three variants were originally planned (see Table 21): the A350-800, the A350-900 (to be developed first), and the A350-1000 [145]. Demand has been low for the -800 variant and it seems unlikely to be pursued further.

The A350-900 is the baseline version and first flew on the 14th of June 2013 [145]. An ultra-long range variant was launched on the 13th of October 2015 and is called the 'A350-900ULR' [145]. The ULR first flew on the 23rd of April 2018 [149] and entered service with Singapore Airlines on 22 September 2018 [150]. The extra range is made possible by fuel-system modifications that enable additional fuel to be carried, an increase in MTOW, and aerodynamic enhancements, which include extended winglets [151].

The -1000 is a stretched version of the -900, with a six-frame plug inserted in front of the wing and a five-frame plug aft of the wing. This stretch, along with an increase in MTOW of over 30 tonnes, necessitated strengthening of the airframe, as well as a more powerful engine [152]. Compared with the -900, the wing area is increased by around 4% [145]. This was done by extending the chord of the high-lift devices and the ailerons by about 400 mm [152]. According to Jane's [145], 90% of the wing parts were modified. Another significant change made to manage the higher weights is the switch from four-wheel-bogies to six-wheel-bogies. To house these, the landing gear bay had to be extended by one frame [152].

5.6 The A380

Design work for the world's largest passenger aircraft, the A380, commenced in June 1994. Apart from being the largest, it is also unique amongst modern airliners in that it has a full-length upper passenger deck. It was developed as a challenger to the Boeing 747, which for decades, was the largest civil aircraft in the market.

The A380 programme was officially launched on the 19th of December 2000 and the maiden flight was on the 27th of April 2005 [153]. The aircraft featured many innovations for the time, including new advances in structures, materials, undercarriage, aerodynamics, and systems [153]. Thus far, only one major variant has been produced – the Airbus A380-800. The -800 can nominally carry 525 passengers and has a range of over 8,000 nm (14,816 km). The engine choices are the GP7270 and versions of the RR Trent 900 [153].

The A380, like the 747-8, has not sold as well as was originally hoped. By September 2018, only 331 were ordered [153]. The reasons for these lacklustre sales, which to some extent also apply to the 747-8, are plentiful. They include high purchasing prices (resulting from high production costs) [154], competition from the more efficient long-haul twins (i.e. the 787, A350, and 777), and risk-averse customers not willing to commit, concerned about sufficiently filling the aircraft to capacity [155]. On the 14th of February 2019, Airbus announced that production of the A380 would cease in 2021.

Stretched and neo variants have been considered, but were not pursued further. However, the development of an improved version, called the 'A380-plus', was announced at the 2017 Paris Airshow [153]. The '-plus' upgrade package would have been available from 2020 [156]. Targets for this version included a reduction of 13% in cash operating cost and 4% in fuel consumption, as compared with the baseline -800 [156]. It would have sported new large composite split winglets and upper-belly fairing improvements. Wing-camber modifications, which were to be performed by increasing the height between Rib 10 and Rib 30 by 33 mm, would also have been introduced [156], along with changes in wing twist [156].

6 Payload-range capability evolution strategies

In this section, the evolution strategies (or lack thereof) of the three manufacturers considered above are investigated. For this purpose, the design payload and range capabilities of the different ancestor aircraft and their descendants (or derivative) were plotted for each manufacturer in single combined payload-range diagrams.

Most of the information employed for the diagrams originates from the 'aircraft characteristics for airport planning' documents provided for by the manufacturers for the different aircraft variants. The raw data, along with all references used, can be viewed on line at `https://doi.org/10.17862/cranfield.rd.7123178`. An overview of all the aircraft surveyed is provided in Figure 11, which shows the Maximum Take Off Weight (MTOW) and certification date of the main variants considered.

In the payload-range diagrams, the sequence of ancestor-derivatives is illustrated by means of arrows (pointing from ancestor to descendant). As will be seen, the design payload-range points of the clean-sheet designs are indicated by squares, whereas those of the derivatives are shown with filled dots. Aircraft not yet certified (at the time of writing) are indicated by empty circles. Aircraft that were developed more or less simultaneously are connected by double-pointed arrows. Where two aircraft do not have a direct ancestor-derivative relationship, but it was determined from the literature that substantial design features were indeed reused, this is indicated by brown dashed arrows. Colours are used to indicate different aircraft families or different generations within a specific family. Dashed arrows between an ancestor and derivative indicate that major changes were made, such as new engines or a substantially revised airframe (not just the 'simple' addition of fuselage plugs).

A few points need to be kept in mind when interpreting these plots. These are:

- It is not always clear what the nominal design payload for a specified aircraft was employed by the manufacturer. In general, the authors endeavoured to use the 'typical passenger' loads, if specified. Where it was known that the fuselage length remained unchanged, the passenger load of the ancestor was used, except in cases where internal space was 'made available' by, for example, moving the rear pressure bulkhead further aft. If the design payload mass was not known, the number of passengers was multiplied by 95 kg to estimate this value (a typical value [38, p/ 142]).

- As with the payload, it is not always clear which nominal range was used during design. There are usually also several mass versions for a given type of aircraft — some of which were added after

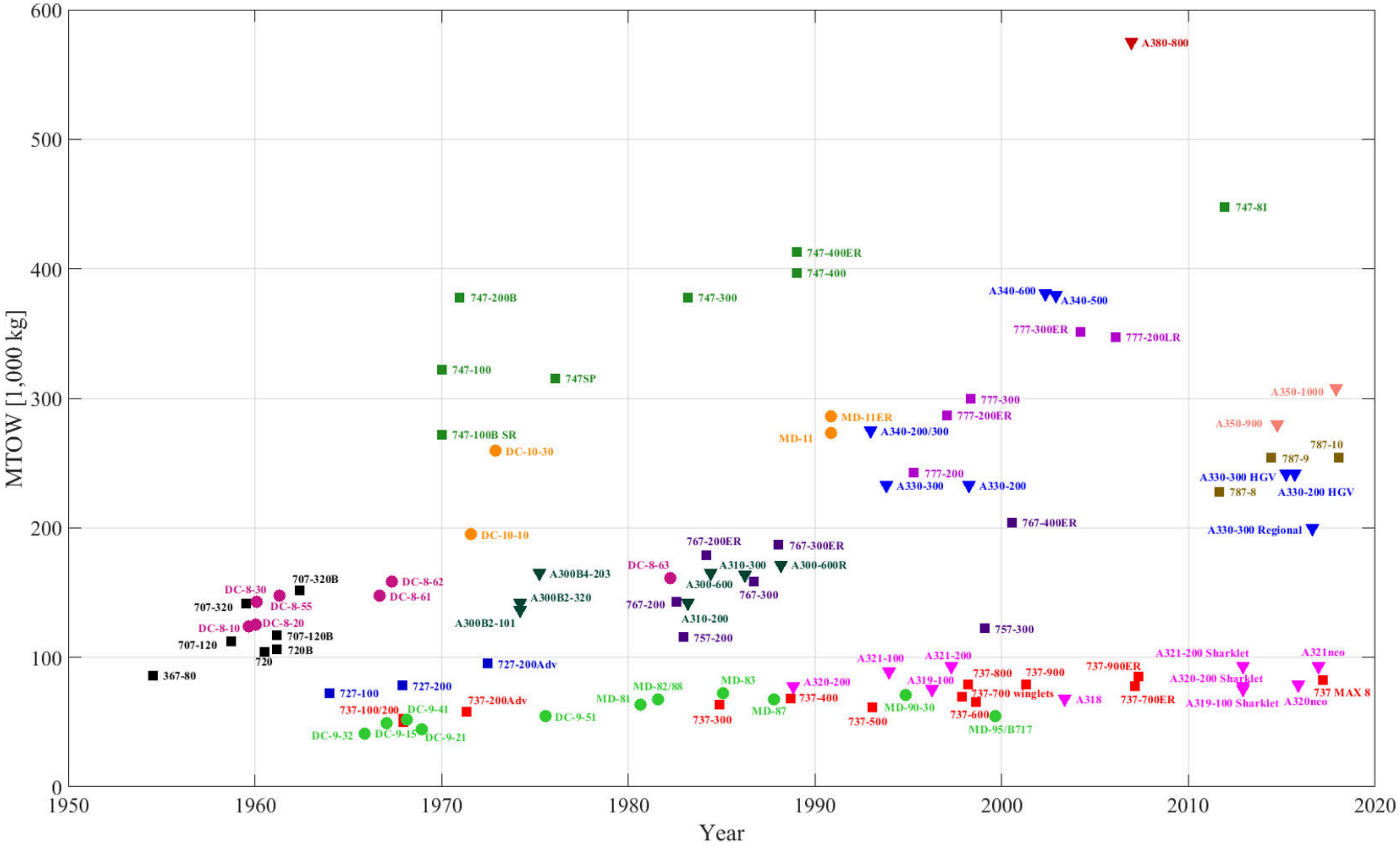
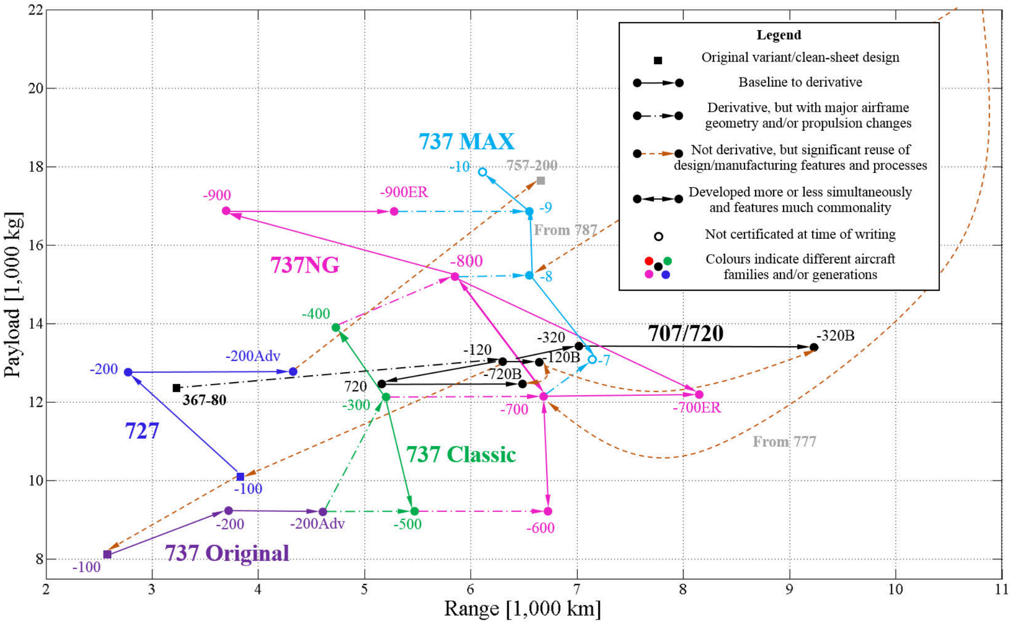


Figure 11: Overview of aircraft surveyed for payload/range evolution and design reuse studies. Shown is the Maximum Take Off Weight (MTOW) and the certification date of each major variant.



	Designation	Certification/EIS		Designation	Certification/EIS		Designation	Certification/EIS
1	367-80	15/07/1954	10	737-100	15/12/1967	19	737-600	18/08/1998
2	707-120	23/09/1958	11	737-200	21/12/1967	20	737-900	17/04/2001
3	707-320	15/07/1959	12	737-200Adv	01/05/1971	21	737-700ER	16/02/2007
4	720	30/06/1960	13	727-200Adv	14/06/1972	22	737-900ER	20/04/2007
5	707-120B	01/03/1961	14	737-300	14/11/1984	23	737-8	08/03/2017
6	720B	03/03/1961	15	737-400	02/09/1988	24	737-9	16/02/2018
7	707-320B	31/05/1962	16	737-500	18/01/1993	25	737-7	2019 (predicted)
8	727-100	24/12/1963	17	737-700	07/11/1997	26	737-10	2020 (predicted)
9	727-200	30/11/1967	18	737-800	13/03/1998			

Figure 12: Boeing single-aisle aircraft payload-range evolution. The table shows the chronology of certification/service entry.

original certification. Therefore, the maximum values for Maximum Take-off Weight (MTOW) were used when determining the range from the payload range diagrams, except in cases where it was known that a higher gross weight variant was added at a specific time (which is often the case for ‘extended range’ variants).

- Should a brown dashed arrow not exist between two points in the plots, it should not be interpreted that there is no design-reuse between these two aircraft. They only indicate that a clear description of significant design reuse was obtained from the literature for the two variants concerned. In reality, no ‘new’ aircraft is truly a clean-sheet development and the manufacturers build on decades of experience, design tools, and manufacturing tooling obtained from previous projects.
- The sequence indicated are based on the certification date for each model. If this was not available, the entry-into-service date was used, which is usually a few days after certification.
- The information in the plots are not exhaustive and not every single variant is covered. The authors did, however, endeavour to cover the main variants of each type.

6.1 Boeing

Two payload-range evolution plots for Boeing aircraft are provided in Figures 12 and 13. The smaller capacity aircraft are covered in Figure 12. The following observations can be made from this plot:

- The 707-120 (and the Dash 80 before it) and 737-100 did not quite have the capacity and range needed when originally pursued. As discussed, even during their respective development periods were their designs adapted to better match market requirements. For the 707, this involved a substantially revised wing, whereas the 737 proved more amenable to change. The 727 did not need such a revision and had only undergone a 'simple' stretch, followed by an increase in range. Therefore, given the ease of their modifications, it therefore seems that the 727 and 737 were designed with growth being considered more than was the case with the Dash-80/707.
- The subsequent evolution of the 737 (from the 737-200Adv onwards) followed a pattern where, for each new generation, there is a substantial increase in payload and/or range, followed by a stretch and a 'virtual' shrink of the fuselage. The word virtual is used, because it is really only a reuse of a previous generation fuselage, but with the airframe modifications of the original member of the new generation. The author will refer to this pattern as 'leap and branch'. It is unlikely that the 737 family was planned as such. The leap often involves disruptive architectural overhaul – a substantial change in wing geometry; structures; fuel capacity; new, or more advanced versions of the engines; and a potential stretch. The 'up-branch' involves a relatively simple stretch, where generally the same airframe geometry as the leap is used with local structural reinforcement. The down-branch features reuse of a previous generation fuselage length, but with the new airframe modifications.
- There is a general increase in both payload capacity and range over time, and the smaller members 'die out'.
- Larger capacity variants are added with each generation, which follows increased market demand for air travel with time.

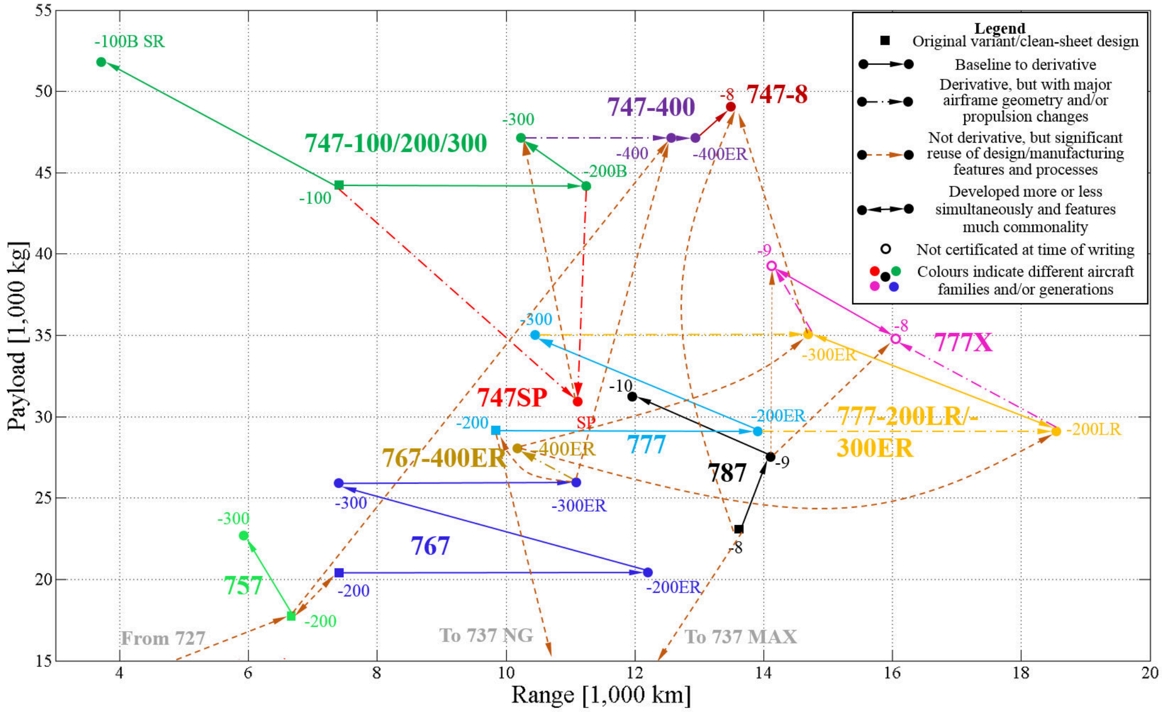
The patterns seem somewhat different with the larger capacity Boeing aircraft, as shown in Figure 13:

- The original 747 seems indeed to at first 'leap and branch' (but here the leap is the original design). The up-branch is, however, not a stretch, but simply an increase in payload at the expense of range. The down-branch represents the significant airframe changes of the 747SP.
- From the original 747 onwards, a distinguishable 'Z' pattern emerges. In this pattern, the range of the baseline is first extended through the addition of fuel capacity, higher gross weights and structural strengthening, followed by a stretch where the increased range is traded for capacity. The authors are aware of at least two sources that refer to this pattern (see Refs [157] and [158]) and it appears that it is Boeing's main strategy for systematically increasing payload and range on their long-haul products. As can be seen, there are a few exceptions, such as the 787, where the 787-9 was significantly modified, as well as the 747-8 and 777X which represent leaps. The documented extensive reuse of 787 design features (as shown by the brown dashed arrows) suggests that significant lessons were learned on the 787. This likely allowed for the improvements incorporated in the 787-9 and the leaps for the 747-8 and 777X.

6.2 McDonnell Douglas

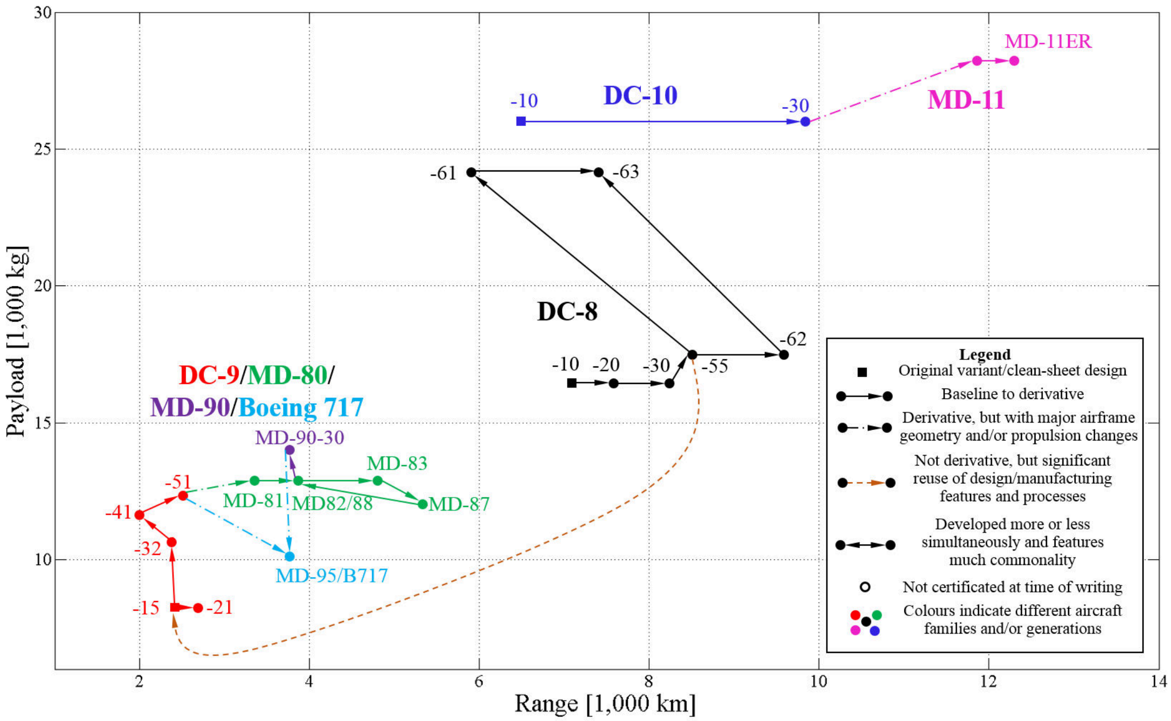
The payload-range evolution plot for McDonnell Douglas airliners is provided in Figure 14. The following observations can be made:

- For its larger aircraft, it seems that McDonnell Douglas usually focused more on increasing range than capacity. The DC-8 retained the same fuselage length for a surprisingly long time, as shown by the horizontal range-extension lines. The eventual stretch of the of the DC-8 (from the -55 to the -61) is substantial and did not require other major airframe modifications. This illustrates how amenable it was to growth, which makes the delay in the stretch difficult to explain. The later pattern for the DC-8 matches the 'Z' observed with larger Boeing aircraft.



	Designation	Certification/EIS
1	'747-100	30/12/1969
2	'747-100B SR	30/12/1969
3	'747-200B	23/12/1970
4	747SP	04/02/1976
5	767-200	30/07/1982
6	757-200	21/12/1982
7	747-300	07/03/1983
8	767-200ER	01/03/1984
9	767-300	22/09/1986
10	767-300ER	20/01/1988
11	747-400	10/01/1989
12	747-400ER	10/01/1989
13	777-200	19/04/1995
14	777-200ER	17/01/1997
15	777-300	04/05/1998
16	757-300	27/01/1999
17	**767-400ER**	**20/07/2000**
18	**777-300ER**	**16/03/2004**
19	**777-200LR**	**01/02/2006**
20	787-8	26/08/2011
21	747-8I	14/12/2011
22	787-9	13/06/2014
23	787-10	22/01/2018
24	777-9	2020 (predicted)
25	777-8	2020 (predicted)

Figure 13: Boeing medium-to-large aircraft payload-range evolution. The table shows the chronology of certification/service entry.



Designation	Certification/EIS	Designation	Certification/EIS	Designation	Certification/EIS
1 DC-8-10	31/08/1959	9 DC-9-41	27/02/1968	17 MD-83	01/02/1985
2 DC-8-20	19/01/1960	10 DC-9-21	11/12/1968	18 MD-87	21/10/1987
3 DC-8-30	01/02/1960	11 DC-10-10	29/07/1971	19 MD-88	31/07/1981
4 DC-8-55	01/05/1961	12 DC-10-30	21/11/1972	20 MD-11	08/11/1990
5 DC-9-15	23/11/1965	13 DC-9-51	01/08/1975	21 MD-11ER	08/11/1990
6 DC-8-61	02/09/1966	14 MD-81	26/08/1980	22 MD-90-30	16/11/1994
7 DC-9-32	27/01/1967	15 MD-82	31/07/1981	23 MD-95/B717	01/09/1999
8 DC-8-62	27/04/1967	16 DC-8-63	01/04/1982		

Figure 14: McDonnell Douglas aircraft payload-range evolution. The table shows the chronology of certification/service entry.

- In contrast to the DC-8, the pattern for the DC-9 consists of a number of large consecutive leaps. These followed one another in close succession and could be attributed to attempts to keep up with the competition from the Boeing 737.
- With the MD-80 series, the focus was again on increasing range, rather than capacity. With the MD-90, capacity is increased again, possibly to compete with the newer Boeing and Airbus models.
- The MD-95 (Boeing 717) is a substantial shrink, indicating that Boeing targeted the market segment below the 737 with this aircraft. As discussed before, this did not work well, and the 717 might have been a shrink too much, being unable to compete with aircraft optimised for this segment.

6.3 Airbus

The payload-range evolution plot for Airbus aircraft is shown in Figure 15. The following observations can be made:

- Airbus also generally follows the leap-and-branch method, but both for its smaller and larger aircraft. The A320 family clearly follows this pattern, but the leaps are done with fewer substantial airframe changes than the 737. This is likely because the A320 was planned as a family from the outset and that Airbus learned from Boeing's early experiences with the 737. As with the 737, the smaller variants 'die out' with time.
- The A330/A340 is an interesting leap, as it constitutes the introduction of two different engine configurations.
- Exceptions to the leap-and-branch pattern include the A300 and A310 families, where the focus seemed to be more on increasing range and filling a niche gap in the market (for the A310). Another exception is the A350, where the changes to create the A350-1000 were rather significant. This is similar to the jump from the 787-8 to the 787-9. Finally, there is little evolution activity for the A380, which reflects the relatively low demand for this aircraft.

6.4 Final Notes on Payload-Range Evolution

The payload-range evolution plots (especially for Boeing and McDonnell Douglas) show a shift from somewhat ad hoc to more systematic design upgrade patterns over time. This shift was well established by the late 1970s to early 1980s. This might be because lessons have been learned and the manufacturers plan better for evolution. It might also, however, reflect the fact that there are fewer competitors and therefore less need to adapt as aggressively as was done in the sixties.

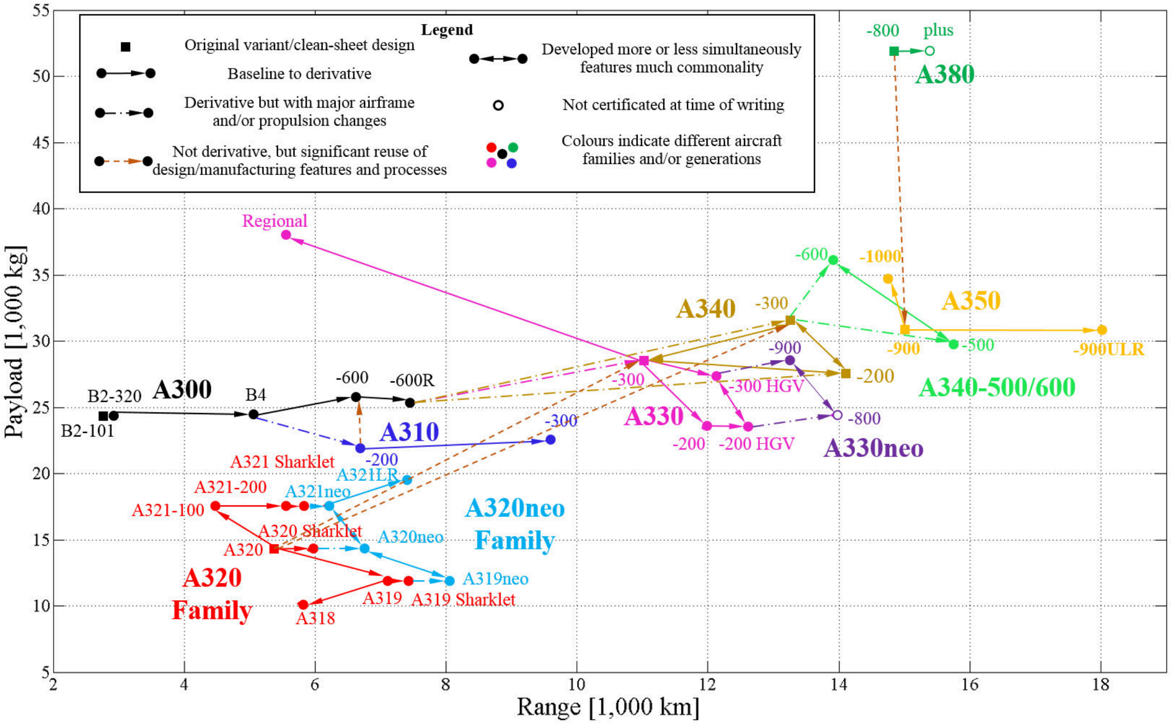
It is also interesting to note that the 787 and A350 evolution patterns differ slightly from those of their predecessors. This might be because these aircraft constituted rather substantial leaps and the experience gained enable more substantial improvements to their derivative than aircraft that have been around for longer.

7 Design changes by payload-range modification objectives

In this section, the major design changes are summarised and classified according to the design objectives that the manufacturers set for derivatives. For this purpose, the data collected for the payload-range evolution plots, discussed in the previous sub-section, along with all the information provided in the previous discussions on the individual aircraft families. The raw data employed in this section, along with references used, can be viewed on line at `https://doi.org/10.17862/cranfield.rd.7123178`.

Payload-range modification objectives for derivative designs can generally be classified into the following:

1. Increase range, keep nominal payload constant. This will usually require an increase in fuel capacity, an increase in MTOW, and structural strengthening.
2. Increase range and increase nominal payload. This usually involves a stretch, an increase in fuel capacity, an increase in MTOW and structural strengthening, and possibly significant airframe changes. This type of change would usually be considered a leap.
3. Decrease payload capacity, increase/decrease range. This usually requires shortening of the fuselage. MTOW could be kept the same, which will enable an increase in range, or it could be lowered to reduce range.
4. Increase payload capacity at the expense of range. This is usually done with local strengthening and inserting plugs to stretch the fuselage, while keeping the MTOW little changed. This type of change usually constitutes a simple 'stretch'.



	Designation	Certification/EIS
1	A300B2-101	15/03/1974
2	A300B2-320	15/03/1974
3	A300B4-203	26/03/1975
4	A310-200	11/03/1983
5	A300-600	01/06/1984
6	A310-300	01/04/1986
7	A300-600R	10/03/1988
8	A320-200	08/11/1988
9	A340-200	22/12/1992
10	A340-300	22/12/1992
11	A330-300	21/10/1993
12	A321-100	17/12/1993
13	A319-100	10/04/1996
14	A321-200	24/04/1997
15	A330-200	31/03/1998
16	A340-600	29/04/2002
17	A340-500	03/12/2002
18	A318	23/05/2003
19	A380-800	12/12/2006
20	A321 Sharklet	01/12/2012
21	A320 Sharklet	01/12/2012
22	A319 Sharklet	01/12/2012
23	**A350-900**	**30/09/2014**
24	A330-300 HGV	01/04/2015
25	A330-200 HGV	08/09/2015
26	A320neo	24/11/2015
27	A330 Regional	18/08/2016
28	A321neo	15/12/2016
29	**A350-1000**	**21/11/2017**
30	**A350-900ULR**	**22/09/2018**
31	A330-900	26/09/2018
32	A321LR	02/10/2018
33	A319neo	21/12/2018
34	A330-800	2019 (predicted)
35	A380plus	2020 (predicted)

Figure 15: Airbus aircraft payload-range evolution. The table shows the chronology of certification/service entry.

Table 22: Development times for different types of derivative payload-range modification objectives.

Objective			Development duration [months][a]		
Payload	Range	No. of aircraft surveyed	Average	Longest	Shortest
Baseline design		15	53.5	93 (A350-900)	27 (B367-80)
Const.	↑	19	32.8	66 (B737 MAX 8)	12 (B737-700ER)
↑	↑	14	46.9	73 (B747-8)	24 (DC-9-51)
↓	↑↓	8	38.8	56 (A310-200)	28 (A330-200)
↑	↓	11	33.1	55 (B787-10)	17 (DC-8-61)
↑[b]	↓	1	35	N/A	N/A

[a] Duration between launch date and certification or EIS date.
[b] No stretching.

5. Increase capacity without stretching and reduce range. This is usually for regional variants of large aircraft, such as the 747-100SR and A330 Regional which are optimised for short-range, high-density routes. Structural strengthening is usually applied to lengthen fatigue life, but the MTOW is lowered substantially.

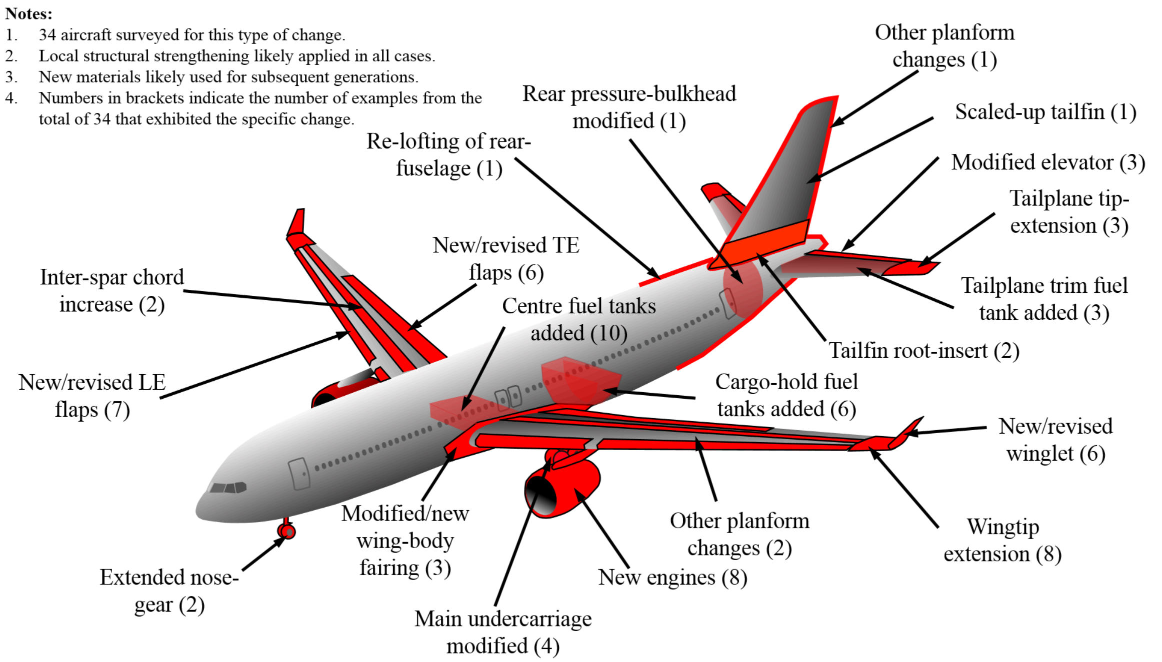
The derivative aircraft surveyed in this study were classified into each of the above categories. The number of derivatives in each group that had a certain type of change applied to it from its baseline (such as a tip extension) was then noted. Considered together with the number of aircraft in the category, this number reflects the frequency at which the type of change was applied as one of the means to achieve the particular payload-range modification objective.

Additionally, the average development time (in months) of the derivatives in each modification objective category was also calculated. The development is assumed to stop at the certification date for each model. If this was not available, the entry-into-service date was used, which is usually a few days after certification. The 'go-ahead', launch, or first order dates were employed as the start of development. The duration in months between these and the certification dates was then used to obtain a rough estimate of the development time for the different aircraft. This is crude at best but determining the exact time a particular aircraft was conceived of for the first time is practically impossible using publicly available records. The average development times calculated only reflect data for aircraft where a launch, go-ahead, or EIS date could be found.

This development time information is provided in the following table and the change type information are shown in the images in the following subsections. In these figures, the changes applied to the baseline to create the derivative are shown in red. The number in brackets next to each change description is the number of derivative examples in the category that exhibited that specific adaptation.

Caution should be applied when interpreting the results in Table 22, as only a selection of aircraft is included, and the development times are rough estimates (as discussed previously). In addition, it is difficult to determine how much resources were used for each program, which makes comparison somewhat dubious. The discussion and conclusions below should therefore be read with these caveats in mind.

However, the results do match what would be expected for the different payload-range modification objectives. For example, the baselines surveyed together had the highest average development time of 53.5 months, which supports the 'common-sense' notion that it is more difficult and expensive to develop an aircraft from scratch. The second highest average was for derivative modification objective 2 (Leaps), which reflects the difficulty associated with the more substantial changes applied to increase both range and capacity. The lowest average development times found are for objectives 1 (extending range, but keeping capacity the same) and 4 (simple stretches). As will be discussed below, this could be because there are relatively fewer changes to the wing and undercarriage (the derivatives that do



Notes:

1. 34 aircraft surveyed for this type of change.
2. Local structural strengthening likely applied in all cases.
3. New materials likely used for subsequent generations.
4. Numbers in brackets indicate the number of examples from the total of 34 that exhibited the specific change.

Figure 16: Design changes for increasing range, maintaining payload.

have changed wings and undercarriage are actually more appropriately classified as leaps, but where there was only an increase in range).

As can also be seen from the table, the spread between minimum and maximum development duration are substantial. It was noted that development times have substantially increased since the sixties. More discussion regarding the data in Table 22 and the changes found for the associated objectives are provided in the following subsections.

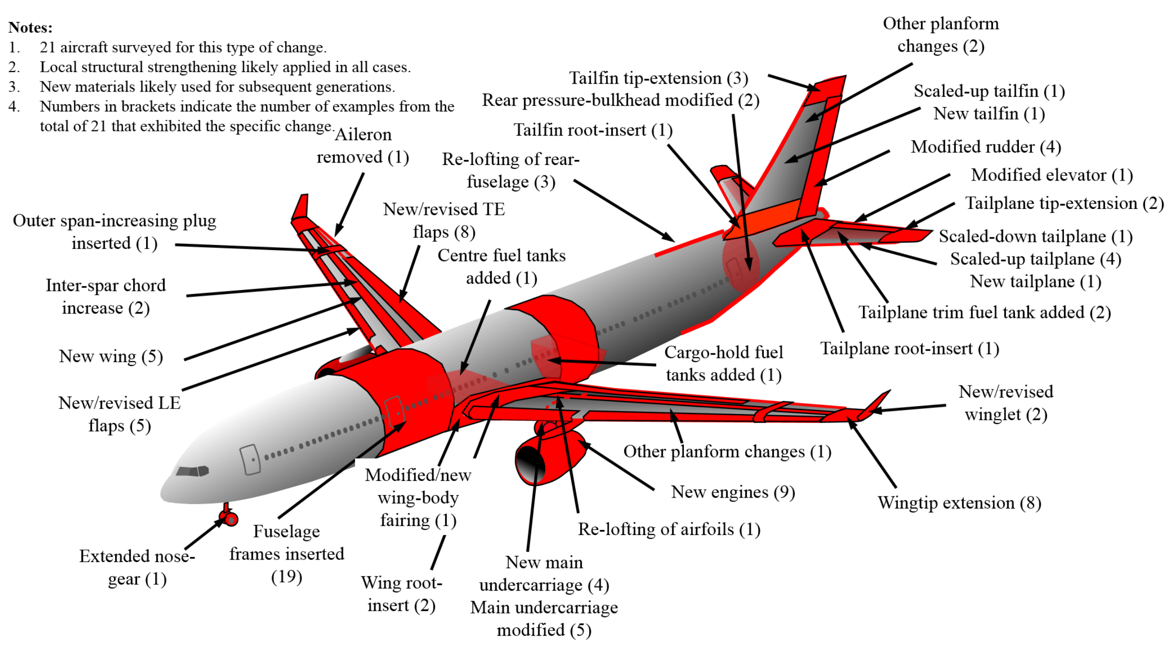
7.1 Increase Range, keep Payload Constant

The major design changes for this objective, which seems to be a common goal, are summarised in Figure 16. As can be seen, most of the changes involve providing additional fuel capacity, along with aerodynamic and structural changes to handle the associated increase in weights.

The most frequent change is the addition of centre fuel tanks. This is expected, because, to provide wing bending-relief, aircraft are usually designed with fuel tanks in the wings first [26, pp. 853-855]. As it becomes clear that more range is needed, the empty space in the centre-section of the wing becomes the obvious next location to house fuel, because of its close proximity to the centre of gravity. From there on, fuel is sometimes housed in additional tanks in the cargo-hold or in tanks integrated within the horizontal stabiliser, which can then also be used as trim tanks for longitudinal stability purposes.

Other frequent changes for this objective include new engines, new or revised high-lift devices, the addition of winglets, and/or the addition of cargo-hold fuel tanks. The modified flaps reflect the need to keep field-length performance for the higher mass derivatives within requirements. Field-length reduction would also be provided by higher thrust, which in some cases are provided by a change in the engine thrust-rating or by a brand-new engine. Also, local airframe strengthening is frequently applied for this objective (a confirmation of this was found for almost every aircraft surveyed in this group), especially to the undercarriage.

Finally, the average development duration for this group was calculated to be the lowest amongst all the groups, suggesting that this is a relatively ‘easy’ objective to achieve. However, this would depend


Notes:

1. 21 aircraft surveyed for this type of change.
2. Local structural strengthening likely applied in all cases.
3. New materials likely used for subsequent generations.
4. Numbers in brackets indicate the number of examples from the total of 21 that exhibited the specific change.

Figure 17: Design changes for both increasing range and payload.

on whether the change is considered a 'simple' increase in range, such as with extended-range (ER) variants, or a leap. This becomes clear when considering the maximum duration found, i.e. that of the 737 MAX 8, which is comparatively high. Indeed, the MAX 8 is the only aircraft surveyed in this group considered to be a leap, and received extensive changes, including a re-lofted rear-fuselage, new engines, and substantial modifications to the undercarriage (see Section 3.5.4).

7.2 Increase Range and Payload

This is also a common objective and is the one in which the most significant changes were found (see Figure 17). This is why many of the derivatives in this group could be considered 'leaps'. As would be expected, the most frequent change is stretching the fuselage by means of a forward and aft plug, but, with some aircraft, additional passenger capacity was made available by increasing internal volume by re-lofting the rear fuselage and by moving the aft pressure bulkhead rearwards (see, for example, the descriptions of Airbus A300-600 and DC-8-50). Other frequent changes for this group often involved the following:

- The addition of new engines (for higher thrust and to exploit improvements in fuel-efficiency). If the engines were not new, more advanced versions and higher thrust engines of the same type were usually employed.
- An increase in wing area (which provides more room for fuel and a larger wing area to keep field-length performance acceptable). From the aircraft surveyed this was most frequently done by means of wingtip extensions, but also sometimes through inter-spar chord-extensions (for example the A340-500 and A340-600) and root-inserts (e.g. the MD-80 series). A completely new wing was introduced in some cases (e.g. the original A330/A340 family).
- The incorporation of new, or the modification of existing flaps (also for maintaining field-length performance).

- New, or modified undercarriage, for increased strength, but in some cases also to lengthen it to make room for larger engines and/or the longer fuselage to maintain clearance at rotation during take-off;
- Enlarging the empennage surfaces to maintain stability and control authority. This was usually achieved through either tip-extensions or root-inserts, and in some cases enlarged control surfaces or the scaling-up of the whole surface.

Other changes are similar to those found for objective 1 and it was also frequently found that local structural strengthening was applied through the thickening of material gauges.

As can be seen from Table 22, the development times in this group are not much lower than for baseline clean sheets and, in several instances, the derivative actually took longer to develop than its baseline. Examples of cases such these are the Boeing 737-300 (with the 737-200Adv as baseline) and 747-8 (747-400ER), the McDonnell Douglas MD-90 (MD-83/MD-87) and MD-11 (DC-10-40), as well as the Airbus A340-200/-300 (A300-600R). These relatively long development times could definitely be explained by the substantial upgrades in propulsion and changes to the wing, as described above, but advances in avionics and systems across generations (not discussed here) contribute as well. It would, therefore, be incorrect to assume that these cases imply that there is little benefit in using a previous design as a baseline, as there are no appropriate equivalent clean sheet designs to compare them with. Additionally, the increase in development time matches an overall increase in aircraft development times across generations, as explained earlier. However, reducing effort and expenses for this objective should be the focus of continued research, especially with regard to embedding change-capability for this objective at the conceptual design of new clean sheet aircraft designs.

There were aircraft found in this group which had comparatively shorter development periods, such as the DC-9-32 and DC-9-51. These aircraft are not quite considered leaps (as the same technology is employed as for their baselines), but also not quite ‘simple stretches’ (as the MTOW and range increased along with the increase in capacity).

7.3 Decrease Payload, increase/decrease Range

To some extent, this objective is the complete opposite of the one explained above. However, the average development time found is the second longest of all the payload-range modification objectives.

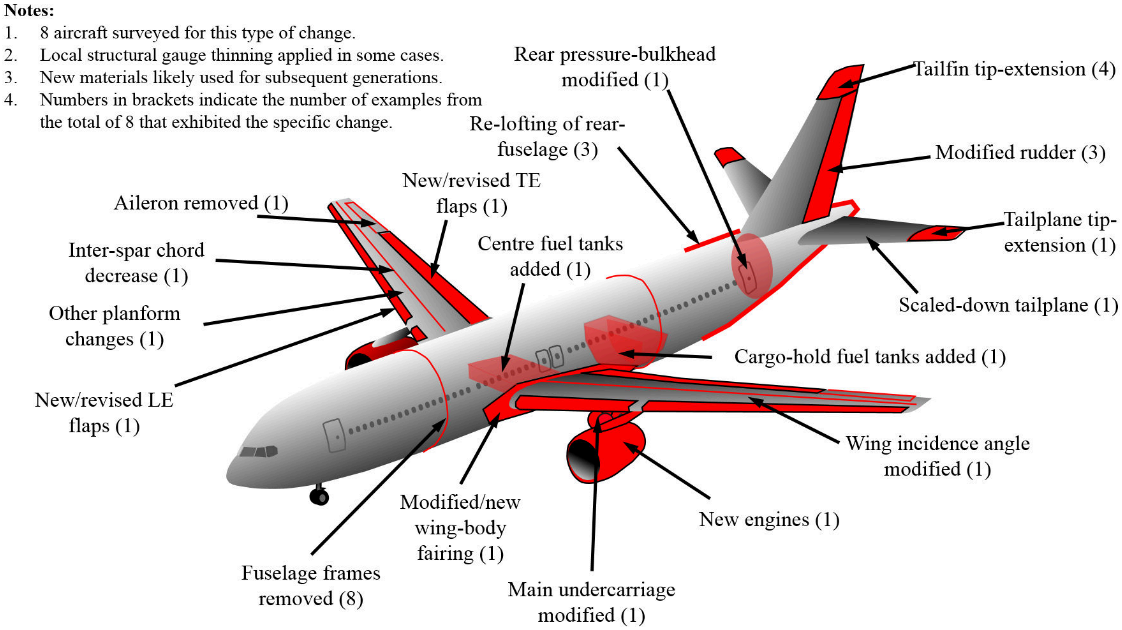
The changes for this group are summarised in Figure 18. As can be seen, fuselage frames were removed in all cases to reduce the length. Re-lofting of the rear-fuselage is also relatively common – improving aerodynamics and making available additional space in the cabin (in the case of the A310). In half of the cases investigated, the tailfin span was increased by introducing a tip-extension, compensating for the reduced moment-arm associated with the shorter fuselage.

The relatively high average development time suggests that these changes are difficult to achieve. The average is somewhat biased by the relatively long development period of the A310, though, where the wing chord was made shorter, constituting a major engineering undertaking. This objective is relatively uncommon.

7.4 Increase Payload at Expense of Range

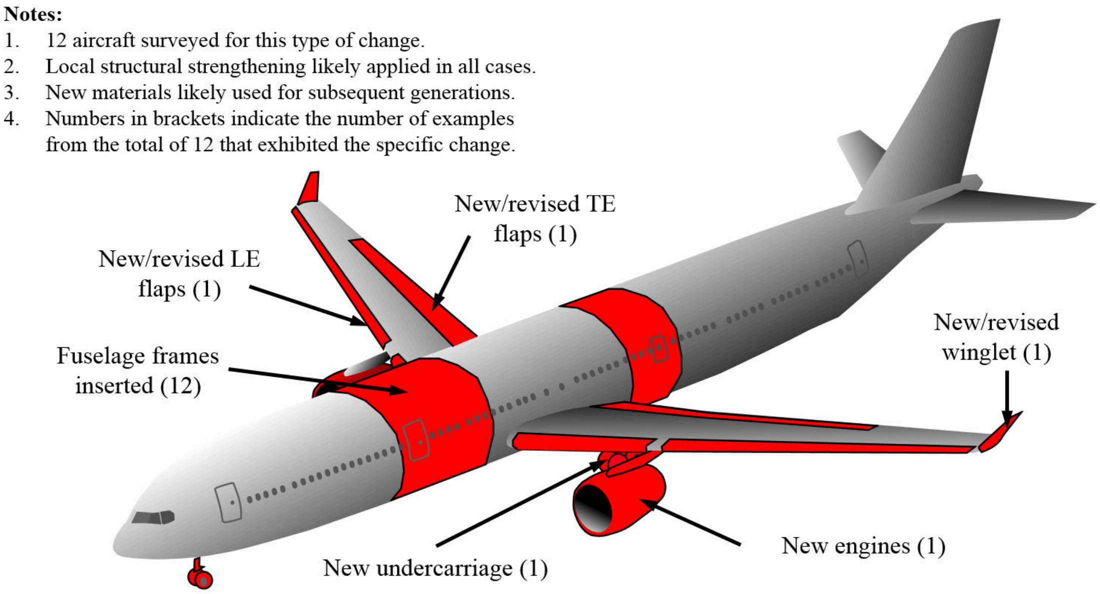
This is the group in which ‘simple stretches’ are found (lengthening the fuselage with ‘minor’ other airframe and propulsion changes). As can be seen in Figure 19, the insertion of fuselage plugs might be accommodated by changes in flaps (to manage possible small increases in weights), winglets, the undercarriage, and new engines, but such changes are relatively rare.

From Table 22, it can be noted that the development periods are comparatively short for this objective, suggesting that may be relatively easier to achieve than others. The longest development period found was for the 787-10, which, again, matches an increase of average development time of airliners over the past decades.



Notes:
1. 8 aircraft surveyed for this type of change.
2. Local structural gauge thinning applied in some cases.
3. New materials likely used for subsequent generations.
4. Numbers in brackets indicate the number of examples from the total of 8 that exhibited the specific change.

Figure 18: Design changes for decreasing payload, increasing range.



Notes:
1. 12 aircraft surveyed for this type of change.
2. Local structural strengthening likely applied in all cases.
3. New materials likely used for subsequent generations.
4. Numbers in brackets indicate the number of examples from the total of 12 that exhibited the specific change.

Figure 19: Design changes for design increasing payload at the expense of range.

7.5 Increase Payload without Stretching and Reduce Range

Drastically reducing range while increasing payload with no stretching is an uncommon endeavour. It essentially involves local strengthening of the structure, but at the same time lowering the MTOW and de-rating the engines. The purpose is to increase payload (but through filling in more seats in an unchanged cabin, rather than a stretch) and increase fatigue life for shorter, more-frequent high-capacity flights. Development duration information could only be obtained for the A330 regional, which seemed somewhat long (35 months). Again, this might simply reflect that fewer resources were devoted to this type during its development.

8 Maximum Changes

In this section, a list of the most substantial airframe modifications identified in this paper is provided together with the maximum increase/decrease in the geometric parameter values associated with each change. As no published information could be found that state when a specific type of design change is impractical (as compared with a new design) the maximum values identified here could be considered to be the maximum 'reasonable changes'. The changes are summarised in Table 23. Note that the maximum values shown are for components which were inherited from the baseline aircraft and subsequently modified – not new components.

Table 23: Maximum parameter value changes for aircraft surveyed.

Description	% Change	Derivative	Baseline
Fuselage length increase	23.00%	DC-8-61	DC-8-50
Fuselage length decrease	21.50%	747SP	747-100
Wingspan increase	18.70%	737NG	737 Classic
Wingspan decrease	2.10%	A310-200	A300B4
Wing 1/4 chord sweep increase	1.5°	A340-600	A340-300
Wing chord length increase at tip	26.54%	737NG	737 Classic
Wing chord length decrease at tip	24.64%	A310-200	A300B4
Wing chord length increase at root	16.00%	A340-600	A340-300
Wing chord length decrease at root	16.16%	A310-200	A300B4
Vertical tail area increase	17.41%	737NG	737 Classic
Horizontal tail area increase	27.50%	A340-600	A340-300
Horizontal tail area decrease	7.85%	A310-200	A300B4
Main undercarriage length increase (based on track)	9.37%	737NG	737 Classic

As can be seen in Table 23, some of the changes are large. Particularly interesting is the large modifications to chord for the Boeing 737NG, Airbus A310-200 and A340-600. The percentage change in chord at the tip was calculated by using the tip chord of the aircraft with the shorter span wing and the chord at the span location of the shorter wing on the longer wing.

Regarding large increases in fuselage length, it should be noted that the length increase from the original 737-100 to the latest 737MAX10 (i.e. ignoring progressive step-increases) is an incredible 51%, whereas the DC-9 to MD-90 length increase is 46%. Another notable aircraft family in this regard is the Bombardier CRJ Series. The length increase from the Bombardier CRJ-100 to CRJ-1000 is also 46%

(see Refs. [159] and [160]), although it should be noted that, once again, this has been implemented progressively. It could be argued that these aircraft were stretched 'too far'. Increasing the fineness ratio (the ratio of length to maximum width of the fuselage) too much, eventually results in drag and structural weight penalties that could render an aircraft with a significantly stretched fuselage less able to compete with comparable aircraft optimised for the same type of mission.

9 Conclusions

The purpose of this research was to characterise the techniques and strategies employed by the major civil jet transport aircraft manufacturers to evolve their existing designs. To do this, the main products of three western manufacturers, namely Boeing, McDonnell Douglas, and Airbus were investigated in depth.

In the early jet-age (1950s and 60s), it seemed that the approach to derive derivative designs was somewhat ad hoc and substantial design changes were frequent. Later, two distinguishable patterns started to appear. The first is what the authors refer to as 'leap-and-branch', where a 'leap' (a new aircraft, or a major derivative) is followed by a 'branch' upwards (a stretch at the expense of range) and a branch-down (a shrink, gaining range). The branches often involve re-using the fuselage and other features from the previous generation, in addition to the airframe upgrades of the leap member. The second pattern is a 'Z' shape, where the range of the baseline is systematically increased, followed by a stretch where the range gained is traded for payload. The description of the Boeing 777 in Nield [157], confirms that the 'Z' pattern and branches is envisioned from program inception (at least for Boeing), but it appears that derivative 'leaps' were not always planned for. The patterns undoubtedly appear because the manufacturers try to meet diverse customer needs and to incorporate new technology that becomes available, but it also became clear throughout this study that it is driven extensively by competition (especially with derivative leaps).

The studies highlight a few lessons learned by the manufacturers (from their own experience as well as from that of their competitors). These relate to:

- Designing products from the outset as a family of aircraft makes evolvability a concrete consideration during conceptual design. This improved the ability of aircraft to evolve. For example, consider the early major Boeing 707 wing modifications vs. almost no external changes in the Airbus A320 family across generations. Family design is now an established approach and it is unlikely that any major new aircraft programme will be conceived as a single-member endeavour.

- The importance of leaving margin in wing area. The original 707-120 did not have the wing area to successfully compete with the DC-8, which led to major changes being made to its wing to devise the 707-320. This lesson was clearly learned by Boeing, as can be seen when studying the wing areas of its subsequent products, especially the 727, 757/767, and 777, which were much larger than needed for the baseline family members. Wing volume is also important. Airbus left significant additional volume in the wing of the A300, which enabled astounding increases in range, without any major changes to the external geometry of the wing. However, too much excess area/volume could, of course, render the baseline unable to compete, and a balance should be obtained (which is difficult to determine) . It is better to redesign the wing for a derivative than have the baseline fail. This performance/commonality trade-off applies to all evolavbility enabler considerations.

- Designing undercarriage for weight and fuselage length increases, as well as larger engines. Considering the 707 again, its undercarriage was not long enough to allow its fuselage to be easily stretched (as opposed to the DC-8). The undercarriage of the 737 was also too short, making it exceedingly difficult to re-engine and stretch the fuselage (esp. to the length of the MAX10). Boeing therefore ensured that their subsequent products have ample landing gear length. Airbus also heeded this lesson, as can especially be observed with the relatively long landing gear legs of the A320 (as opposed to those of the 737). Boeing also learned from McDonnell Douglas's experience with the DC-10-10 undercarriage. The DC-10 design had to receive an extra landing gear leg to handle the higher weight of the -30 model, whereas the Boeing 777 was provided with six-wheel bogies that spread the load more evenly, allowing for considerable growth in weight.

- The importance of configuration. Configuration can have a significant impact on evolvability. The 'tube-and-wing' and 'podded engine' architectural philosophies promote both the evolvability principles of 'modularity' and 'independence'. These facilitate change by limiting extensive modifications to only those components that are desired to be changed. This factor, along with the use of a simple tubular construction for modern fuselages, which makes them particularly amenable to stretching and shrinking (i.e. scalable), may explain a general reluctance of the airframe manufacturers to diverge from the dominant conventional configuration. Also, the short, wide fuselage and engines-under-wing configuration of the 737 made it more amenable to have its fuselage stretched than the T-tail, fuselage-mounted engine configuration of the DC-9. Evolvability should therefore be an important consideration when selecting the configuration for a clean sheet design.
- Structural strengthening is reasonably easy to achieve, but substantial geometry changes (especially to the wing) not so much.
- Developing a smaller derivative is often more difficult than a larger one. This can be appreciated when considering the 'architecture overhaul' type of changes seen with the A300 to A310 and 747-100 to 747SP.
- There are often multiple ways to achieve a desired outcome for a derivative. For example, changing internal cabin layout and the location of pressure bulkheads could be considered instead of stretching the fuselage (as was done with the DC-8 and A300). All options should therefore be studied.
- Sometimes, opting for a clean-sheet design is better than evolving an existing one, as commonality often comes at the expense of performance. For example, although there are several reasons for the lacklustre success of the A340, one contributing factor may have been the increase in wing area for the -500/600 models by inserting a wedge, instead of designing a new, optimised wing (or indeed a brand new aircraft). Clean sheet developments are expensive and risky, but the result could be a superior product and the manufacturer could exploit the lessons learned on all subsequent endeavours (as was done by Boeing, reusing practices and design features developed for the 787 on the 747-8, 737MAX, and 777X, and by Airbus, exploiting A380 expertise on the A350 and A330neo).

Perhaps the most important lesson was simply to recognise the importance of extensively studying the future market and planning appropriately for change. Unfortunately, this is of course not easy, as it requires predicting the future (often decades ahead), which involves the study of a large number of scenarios, configurations, technologies, competitor actions, and so forth. This underpins the need for efficient computational methods to support predicting and enhancing evolvability in aircraft (especially during conceptual design). Some work has already been undertaken in this regard (e.g. Refs. [161, 15, 162, 4]), but much more can be done, especially in supporting more efficient and comprehensive computational design space exploration and developing improved decision-making tools.

It would be interesting to observe how the current and future products of Airbus and Boeing (as well as those of newcomers, such as the Commercial Aircraft Corporation of China [COMAC]) will evolve. In the long-haul segment, further stretching of the A350 will depend a lot on the extent of the success of the 777X. Airbus does not yet see the demand for a larger A350 and believes that further engine advances are required first [163]. Conversely, Boeing has studied further stretching of the 777-9, and believes such a change would be 'simple' to implement [164]. Other future developments on the 787, A350, 777, and (maybe) the A380 will likely focus on continuous aerodynamic and structural refinement, re-engining, and improving production processes.

Of particular interest will be what the manufacturers will do in the single-aisle and so-called ‘midsize’ segments. Both the 737 and A320 families have evolved significantly and how much further this can be taken is debatable. New single-aisle aircraft will undoubtedly be introduced as multiple-member families and much of the experience gained in the newer long-haul aircraft will probably be exploited in their development.

Boeing is currently actively studying whether to introduce a ‘New Midsize Airplane’ (NMA). Such an aircraft would replace the 757 and compete with the A321, with a range of about 7,400 to 9,260 km and seating 200 to 270 passengers [165]. Not much is yet known publicly of the NMA, but it seems that it will have a ‘hybrid fuselage cross section’ (smaller cargo area with a wider passenger cabin) [165]. Again, if Boeing proceeds, the NMA will likely be introduced as a family and make considerable use of the experience gained with the latest Boeing products. Any new 737 replacement will probably be closely related to this new aircraft, in an arrangement perhaps not unlike the 757/767 programme.

A major focus for follow-up work on the studies presented in this paper would be the investigation of the evolvability of unconventional configurations, as well as evolvability across aircraft that have different configurations (major component layouts). Some descriptions of families of unconventional aircraft have indeed been found in the literature, albeit that all members share the same configuration. One such example is from Liebeck [166] and concerns the description of a family of blended-wing-body passenger aircraft. In this description, Liebeck demonstrates how the wing and cockpit design could be retained across different family members, while inserting bays to increase payload capacity. This would have the effect of automatically increasing span, which is beneficial in terms of countering the additional mass through increased wing area. Another example can be found in Scholz [167], who demonstrated how a box-wing design could be stretched to create additional family members. These studies are essential, and the authors are of the opinion that growth versions should be studied for every novel configuration proposed. However, for manufacturers to adopt new configurations, they would likely prefer to offset the major risks involved (associated with novel configurations) by gradually evolving existing conventional designs to these. More work is required to study how this could be done effectively and affordably.

The evolvability enabler of mimicry (using similar design practices and features from previous products or systems, or other domains) was found to be pervasive across the three manufacturers. The Airbus A300-600’s mimicry of the A310 (adopting the rear fuselage and some wing geometry advances of the A310), as well as the Boeing 747-8, 737 MAX, and 777X’s mimicry of the 787 (extensive incorporation of the 787 composites, aerodynamics, and subsystems advances) are notable examples. Current evolvability design techniques available in the literature do not appear to cater for these possibilities. Future work could therefore also focus on developing design techniques to predict the potential benefits of mimicry with other products in a manufacturer’s product portfolio.

References

[1] O. L. de Weck, A. M. Ross, D. H. Rhodes, Investigating relationships and semantic sets amongst system lifecycle properties (ilities), in: Proceedings of the third international engineering systems symposium CESUN, Delft University of Technology, Delft, The Netherlands, 2012, pp. 1–12.

[2] M. A. Cardin, Enabling flexibility in engineering systems: A taxonomy of procedures and a design framework, Journal of Mechanical Design, Transactions of the ASME 136 (1) (2014) 1–14. URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-84888867927{&}partnerID=40{&}md5=936466bb8128a2b65ffa85ea6eac8c7d`

[3] K. Willcox, S. Wakayama, Simultaneous optimization of a multiple-aircraft family, Journal of Aircraft 40 (4) (2003) 616–622. URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-0042381749{&}partnerID=40{&}md5=209262d95692dff73c077659aa055e25`

[4] A. S. Van Heerden, Computational techniques for aircraft evolvability exploration during conceptual design, PhD Thesis (submitted for examination at time of writing), Cranfield University (2018).

[5] Boeing, Current market outlook: 2017–2036, `http://www.boeing.com/resources/boeingdotcom/commercial/market/current-market-outlook-2017/assets/downloads/2017-cmo-6-19.pdf`, accessed: 2018-05-17 (2017).

[6] M. Rehmet, J. Wolf, Challenges in international co-design and development of a new family of airliners, in: 23rd Congress of the International Council of the Aeronautical Sciences, ICAS, Toronto, Canada, 2002.

[7] E. Fricke, A. P. Schulz, Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle, Systems Engineering 8 (4) (2005) 342–359.
URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-30544446870{&}partnerID=40{&}md5=5c25be5cfd56e4cef05808c6c1a41bda`

[8] A. M. Ross, D. H. Rhodes, D. E. Hastings, Defining system changeability: Reconciling flexibility, adaptability, scalability, and robustness for maintaining system lifecycle value, in: 17th Annual International Symposium of the International Council on Systems Engineering, INCOSE 2007 - Systems Engineering: Key to Intelligent Enterprises, Vol. 2, San Diego, CA, USA, 2007, pp. 735–749.
URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-84878096146{&}partnerID=40{&}md5=cf1934f8f603ee91048827f2c26fe16b`

[9] E. T. Ryan, D. R. Jacques, J. M. Colombi, An ontological framework for clarifying flexibility-related terminology via literature survey, Systems Engineering 16 (1) (2013) 99–110.
URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-84872958220{&}partnerID=40{&}md5=04b54d0d242d85645d4211b293ca3583`

[10] M. Kingsley-Jones, Airbus begins deliveries of first elements of performance improvement package for A320 family, FlightGlobal`https://www.flightglobal.com/news/articles/airbus-begins-deliveries-of-first-elements-of-performance-improvement-package-for-a320-family-2`
Accessed: 2019-01-08.

[11] K. Thomson, E. T. Schulze, Delivering fuel and emissions savings for the 777, Boeing Aero Magazine QTR_3 09.

[12] Boeing, Boeing Next-Generation 737 Performance Improvement Package Delivers on Promise to Cut Fuel Burn, `https://boeing.mediaroom.com/2012-07-31-Boeing-Next-Generation-737-Performance-Improvement-Package-Delivers-on-Promise-to-Cu`
accessed: 2019-01-08 (2012).

[13] American Society of Mechanical Engineers, Wright Flyer III, `https://www.asme.org/about-asme/who-we-are/engineering-history/landmarks/224-wright-flyer-iii`, accessed: 2018-06-14 (2018).

[14] R. J. Francillon, McDonnell Douglas Aircraft since 1920., Alden Press, Oxford, 1988.

[15] D. Lim, A systematic approach to design for lifelong aircraft evolution, Ph.D. thesis, Georgia Institute of Technology (2009).

[16] D. Long, S. Ferguson, A case study of evolvability and excess on the B-52 Stratofortress and F/A-18 Hornet, in: ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, 2017, pp. V004T05A026–V004T05A026.

[17] D. Kellari, E. F. Crawley, B. G. Cameron, Architectural decisions in commercial aircraft from the DC-3 to the 787, Journal of Aircraft 55 (2) (2017) 792–804.

[18] N. P. Suh, Axiomatic design, Oxford University Press, 2001.

[19] A. H. Tilstra, P. B. Backlund, C. C. Seepersad, K. L. Wood, Principles for designing products with flexibility for future evolution, International Journal of Mass Customisation 5 (1) (2015) 22–54.

[20] S. White, S. Ferguson, Exploring architecture selection and system evolvability, in: ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, 2017, pp. V02BT03A044–V02BT03A044.

[21] J. Beesemyer, Empirically Characterizing Evolvability and Changeability in Engineering Systems, Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, USA. (2010).

[22] Z. Pirmoradi, G. G. Wang, T. W. Simpson, A review of recent literature in product family design and platform-based product development, in: T. W. Simpson, R. J. Jiao, Z. Siddique, K. Hölttä-Otto (Eds.), Advances in product family and product platform design, Springer, New York, 2014, pp. 1–46.

[23] J. D. Allen, C. A. Mattson, S. M. Ferguson, Evaluation of system evolvability based on usable excess, Journal of Mechanical Design 138 (9) (2016) 091101.

[24] M. W. P. Tackett, C. A. Mattson, S. M. Ferguson, A model for quantifying system evolvability based on excess and capacity, Journal of Mechanical Design 136 (5) (2014) 51002–51011.
URL `http://dx.doi.org/10.1115/1.4026648`

[25] M. D. Guenov, X. Chen, A. Molina-Cristóbal, A. Riaz, A. S. van Heerden, M. Padulo, Margin allocation and tradeoff in complex systems design and optimization, AIAA Journal (2018) 1–16.

[26] D. P. Raymer, Aircraft Design: A Conceptual Approach, 5th Edition, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2012.

[27] P. Zhuravlev, V. Zhuravlev, Significance of modifications for development of passenger airplanes, Aircraft Engineering and Aerospace Technology 84 (3) (2012) 172–180.
URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-84861356179{&}partnerID=40{&}md5=9b81216869e647fd09e9fede74b670b3`

[28] R. C. Boas, Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, U.S.A. (2008).

[29] B. G. Cameron, E. F. Crawley, Crafting platform strategy based on anticipated benefits and costs, in: T. W. Simpson, R. J. Jiao, Z. Siddique, K. Hölttä-Otto (Eds.), Advances in Product Family and Product Platform Design, Springer, New York, 2014, pp. 49–70.

[30] Boeing, Our company: General information, `http://www.boeing.com/company/`, accessed: 2018-03-12.

[31] R. Redding, B. Yenne, Boeing: Planemaker to the World, Bison Books, London, United Kingdom, 1983.

[32] G. Norris, M. Wagner, Boeing, Motorbooks International, Minneapolis, MN, U.S.A., 1998.

[33] J. E. Steiner, Jet Aviation Development – One Company's Perspective. The Last Forty Years and a Brief Look at the Future, in: Presented at the National Air and Space Museum, Smithsonian Institution, October 1979, Seattle, WA, U.S.A., 1979.

[34] J. Winchester, Airlife's Classic Airliners: Boeing 707/720, Airlife Publishing Ltd, United Kingdom, 2002.

[35] B. Almojuela, The development of Boeing's 367-80, airplanes Pacific Northwest AIAA Technical Symposium (2009).
URL https://www.slideshare.net/skyben77/the-development-of-boeings-36780-or-charging-into-the-j

[36] Jane's by IHS Markit, Boeing 707, https://janes.ihs.com/Janes/Display/jau_1412-jau_, accessed: 2018-06-29 (2018).

[37] Flight, Commercial aircraft of the world, Flight (1959) p. 582https://www.flightglobal.com/pdfarchive/view/1959/1959%20-%203057.html. Accessed: 2019-01-21.

[38] L. R. Jenkinson, P. Simpkin, D. Rhodes, Civil jet aircraft design, Arnold, London, 1999.

[39] Boeing Commercial Airplanes, Airplane characteristics for airport planning, https://www.boeing.com/commercial/airports/\plan_manuals.page, accessed: 2018-06-01 (2018).

[40] L. K. Loftin Jr., Jet transports, in: Quest for Performance: The Evolution of Modern Aircraft (NASA SP-468), NASA History Office, New York, 1985, Ch. Chapter 13.

[41] Boeing, Orders and deliveries, http://www.boeing.com/commercial/#/orders-deliveries, accessed: 2019-01-14 (2019).

[42] Boeing, CAD 3-View Drawings for Airport Planning Purposes, http://www.boeing.com/commercial/airports/\3_view.page, accessed: 2018-05-30 (2018).

[43] W. Green, G. Swanborough, J. Mowinski, Modern Commercial Aircraft, Salamander Books, London, 1987.

[44] Jane's by IHS Markit, Boeing 720, https://janes.ihs.com/Janes/Display/jau_1413-jau_, accessed: 2018-06-30 (2018).

[45] Boeing, 707/720 commercial transport – Historical snapshot, http://www.boeing.com/history/products/707.page, accessed: 2018-03-07.

[46] Boeing, 727 commercial transport – Historical snapshot, http://www.boeing.com/history/products/727.page, accessed: 2018-03-21.

[47] Jane's by IHS Markit, Boeing 727, https://janes.ihs.com/Janes/Display/jau_1414-jau_, accessed: 2018-06-29 (2018).

[48] A. J. Wright, Boeing 737, Ian Allan Ltd., London, 1991.

[49] Jane's by IHS Markit, Boeing 737, https://janes.ihs.com/Janes/Display/jawa1202-jawa, accessed: 2018-06-01 (2018).

[50] R. Whitford, Evolution of the airliner, Crowood Press Ltd, 2007.

[51] Jane's by IHS Markit, Boeing 737-200, https://janes.ihs.com/Janes/Display/jau_1415-jau_, accessed: 2018-06-29 (2018).

[52] Jane's by IHS Markit, Boeing 737-300, https://janes.ihs.com/Janes/Display/jau_9138-jau_, accessed: 2018-06-29 (2018).

[53] Jane's by IHS Markit, Boeing 737-400, https://janes.ihs.com/Janes/Display/jau_9139-jau_, accessed: 2018-06-29 (2018).

[54] Jane's by IHS Markit, Boeing 737-500, https://janes.ihs.com/Janes/Display/jau_9140-jau_, accessed: 2018-06-29 (2018).

[55] P. Proctor, Lower costs drive next-generation 737, Aviation Week & Space Technology (1996) 68–71.

[56] R. Faye, R. Laprete, M. Winter, Blended winglets for improved airplane performance, Boeing Aero Magazine (17).

[57] Boeing, Boeing launches 737 new engine family with commitments for 496 airplanes from five airlines, `http://boeing.mediaroom.com/2011-08-30-Boeing-Launches-737-New-Engine-Family-with-\Commitments-for-496-Airplanes-from-\Five-Airlines`, accessed: 2018-06-29 (2011).

[58] J. Ostrower, Boeing designates 737 MAX family, FlightGlobal`https://www.flightglobal.com/news/articles/boeing-designates-737-max-family-361428/`. Accessed: 2018-06-29.

[59] F. George, Pilot report: Flying the 737-8, Boeing's new narrowbody breadwinner, Aviation Week & Space Technology`http://aviationweek.com/commercial-aviation/pilot-report-flying-737-8-boeing-s-new-narrowbody-\breadwinner`. Accessed: 2018-06-29.

[60] S. Trimble, Analysis: 737 MAX cutaway and technical description, FlightGlobal`https://www.flightglobal.com/news/articles/analysis-737-max-cutaway-and-technical-description-437370/`. Accessed: 2018-06-29.

[61] G. Norris, Laminar flow boosts 737 MAX long-range performance, Aviation Week & Space Technology`http://aviationweek.com/awin/laminar-flow-boosts-737-max-long-range-performance`. Accessed: 2018-06-29.

[62] T. Hepher, Boeing 737 MAX 7 narrowbody jetliner makes maiden flight, Reuters`https://www.reuters.com/article/us-boeing-737-max-7/boeing-737-max-7-narrowbody-jetliner-makes\-maiden-flight-idUSKCN1GS2CM`. Accessed: 2018-06-29.

[63] Boeing, 737 MAX, `https://www.boeing.com/commercial/737max/#/technical-specs`, accessed: 2019-01-21 (2019).

[64] S. Trimble, Farnborough: Boeing details range-boosting 737-7 redesign, FlightGlobal`https://www.flightglobal.com/news/articles/farnborough-boeing-details-range-boosting-737-7-red-427468/`. Accessed: 2018-06-29.

[65] G. Polek, Boeing upscales 737 MAX 7, Aviation International News`https://www.ainonline.com/aviation-news/aerospace/2016-07-12/boeing-upscales-737-max-7`. Accessed: 2018-06-29.

[66] S. Trimble, Paris: Boeing launches 737 MAX 10, FlightGlobal/`https://www.flightglobal.com/news/articles/paris-boeing-launches-737-max-10-438370/`. Accessed: 2018-06-29.

[67] Boeing, Boeing launches larger capacity 737 MAX 10 at 2017 Paris air show, `http://boeing.mediaroom.com/2017-06-19-Boeing-Launches-Larger-Capacity-737-MAX-10-\at-2017-Paris-Air-Show`, accessed: 2018-06-29 (2011).

[68] Jane's by IHS Markit, Boeing 747-200, `https://janes.ihs.com/Janes/Display/jau_1416-jau_`, accessed: 2018-06-29 (2018).

[69] Jane's by IHS Markit, Boeing 747SP, `https://janes.ihs.com/Janes/Display/jau_1418-jau_`, accessed: 2018-06-29 (2018).

[70] Jane's by IHS Markit, Boeing 747-400, `https://janes.ihs.com/Janes/Display/jau_a146-jau_`, accessed: 2018-06-29 (2018).

[71] Jane's by IHS Markit, Boeing 747-8, `https://janes.ihs.com/Janes/Display/jawaa644-jawa`, accessed: 2018-06-29 (2018).

[72] P. Gilchrist, Boeing 747, Ian Allan, London, 1992.

[73] C. Collisson, Re-inventing the legend: The development of the 747-8, in: 26th International Congress of the Aeronautical Sciences, Anchorage, AK, USA, 2008.

[74] W. G. Loeken, The cost definition phase of a new commercial aircraft programme, The Aeronautical Journal 87 (862) (1983) 68–75.

[75] P. J. Birtles, Boeing 757/767, Ian Allan Ltd, Shepperton, Surrey, 1987.

[76] Jane's by IHS Markit, Boeing 757-200, `https://janes.ihs.com/DefenceEquipment/Display/jau_a059-jau_`, accessed: 2018-06-29 (2018).

[77] Jane's by IHS Markit, Boeing 757-300, `https://janes.ihs.com/DefenceEquipment/Display/jau_a060-jau_`, accessed: 2018-06-29 (2018).

[78] Jane's by IHS Markit, Boeing 767, `https://janes.ihs.com/Janes/Display/jawa1207-jawa`, accessed: 2018-06-29 (2018).

[79] H. Queen, Introducing the 767-400 extended range airplane, Boeing Aero Magazine (3).

[80] G. Norris, Strategic stretch, Flight International (1999) 449–471.

[81] J. Ramsden, Boeing 767 and 777, Flight International (1978) 1472–1474.

[82] P. Eden (Ed.), Civil Aircraft Today: The World's Most Successful Commercial Aircraft, Amber Books, London, 2008.

[83] G. Norris, M. Wagner, Boeing 777, Motorbooks International, St. Paul, Minnesota, 1996.

[84] G. Norris, M. Wagner, Modern Boeing jetliners, MBI Pub. Co., Osceola, WI, 1999.

[85] Jane's by IHS Markit, Boeing 777, `https://janes.ihs.com/Janes/Display/jawa1209-jawa`, accessed: 2018-06-29 (2018).

[86] G. Norris, First flight of 777-200lr kicks off ultra-long-haul test programme, FlightGlobal`https://www.flightglobal.com/news/articles/first-flight-of-777-200lr-kicks-off-ultra-long-haul-195155/`. Accessed: 2018-06-29.

[87] Boeing, 777X by design, `http://www.boeing.com/commercial/777x/by-design#/featured`, accessed: 2018-06-29 (2018).

[88] G. Norris, Long ranger, FlightGlobal`https://www.flightglobal.com/news/articles/long-ranger-160884/`. Accessed: 2018-06-29.

[89] S. Trimble, Dubai: Boeing formally launches 777X family with 259 commitments, FlightGlobal`https://www.flightglobal.com/news/articles/dubai-boeing-formally-launches-777x-family-with-259-393138/`. Accessed: 2018-06-29.

[90] S. Trimble, Boeing reveals ultra-long-range 777-8x, FlightGlobal`https://www.flightglobal.com/news/articles/boeing-reveals-ultra-long-range-777-8x-387108/`. Accessed: 2018-06-29.

[91] G. Norris, J. Anselmo, 777x production investments bolster Boeing, Aviation Week & Space Technology`http://aviationweek.com/commercial-aviation/777x-production-investments-bolster-boeing`. Accessed: 2018-06-29.

[92] S. Trimble, GE9X enters flight test phase, FlightGlobal`https://www.flightglobal.com/news/articles/ge9x-enters-flight-test-phase-446784/`. Accessed: 2019-01-13.

[93] V. Bhaskara, C. Sloan, Boeing 777x program perched precariously despite strong execution, Airways`https://airwaysmag.com/airlines/boeing-777x-trouble-strong-execution/`. Accessed: 2018-06-29.

[94] S. Trimble, FAA sets certification rules for 777X wingtip, FlightGlobal`https://www.flightglobal.com/news/articles/faa-sets-certification-rules-for-777x-wingtip-448708/`. Accessed: 2019-01-13.

[95] C. Shifrin, Dream start, FlightGlobal`https://www.flightglobal.com/news/articles/dream-start-205611/`. Accessed: 2019-01-15.

[96] Boeing, Boeing Launches 7E7 DreamlinerAccessed: 2019-01-15.

[97] Boeing, 787 commercial transport – Historical snapshot, `http://www.boeing.com/history/products/787.page`, accessed: 2019-01-15 (2019).

[98] Jane's by IHS Markit, Boeing 787, `https://janes.ihs.com/Janes/Display/jawa5814-jawa`, accessed: 2018-06-29 (2018).

[99] M. Kingsley-Jones, Analysis: Why Boeing's 787-9 is more than just a stretch, FlightGlobal`https://www.flightglobal.com/news/articles/analysis-why-boeings-787-9-is-more-than-just-a-str-401110/`. Accessed: 2018-06-29.

[100] Boeing, 787 by design, `https://www.boeing.com/commercial/787/by-design/`, accessed: 2019-01-21 (2019).

[101] G. Norris, Simplicity is vital to Boeing 787-10 execution, Aviation Week & Space Technology`http://aviationweek.com/commercial-aviation/simplicity-vital-boeing-787-10-execution`. Accessed: 2018-06-29.

[102] S. Trimble, Analysis: Boeing 787-10 technical description and cutaway, FlightGlobal`https://www.flightglobal.com/news/articles/analysis-boeing-787-10-technical-description-and-cu-446856/`. Accessed: 2018-06-29.

[103] Jane's by IHS Markit, Boeing (Douglas) DC-9, `https://janes.ihs.com/Janes/Display/jau_1428-jau_`, accessed: 2018-06-29 (2018).

[104] Jane's by IHS Markit, Boeing (McDonnell Douglas) MD-80 Series, `https://janes.ihs.com/Janes/Display/jau_9144-jau_`, accessed: 2018-06-29 (2018).

[105] Jane's by IHS Markit, Boeing (McDonnell Douglas) MD-90, `https://janes.ihs.com/Janes/Display/jau_9145-jau_`, accessed: 2018-06-29 (2018).

[106] Boeing, 717/MD-95 commercial transport – Historical snapshot, `http://www.boeing.com/history/products/717-md-95.page`, accessed: 2018-03-06.

[107] Jane's by IHS Markit, Boeing 717, `https://janes.ihs.com/Janes/Display/jau_a092-jau_`, accessed: 2018-06-29 (2018).

[108] Jane's by IHS Markit, Boeing (McDonnell Douglas) DC-10, `https://janes.ihs.com/Janes/Display/jau_1430-jau_`, accessed: 2018-06-29 (2018).

[109] Jane's by IHS Markit, Boeing (McDonnell Douglas) MD-11, `https://janes.ihs.com/Janes/Display/jau_9143-jau_`, accessed: 2018-06-29 (2018).

[110] J. Bailey, J. Marsden, Md-11 enters the fray, Flight International.

[111] H. Hopkins, Masterfully digital 11, Flight International.

[112] L. Marriott, McDonnell Douglas MD-11, Ian Allan Ltd., Shepperton, Surrey, 1992.

[113] Airbus, Orders and deliveries – commercial aircraft, `https://www.airbus.com/aircraft/market/orders-deliveries.html#file`, accessed: 2019-01-20 (2018).

[114] Jane's by IHS Markit, Airbus A300, `https://janes.ihs.com/Janes/Display/jau_a097-jau_`, accessed: 2018-06-30 (2018).

[115] B. Gunston, Airbus, Osprey Publishing Company, London, 1988.

[116] Airbus, A300-600, `https://www.airbus.com/aircraft/previous-generation-aircraft/a300-600.html`, accessed: 2019-01-22 (2019).

[117] Airbus, Aircraft characteristics: Airport operations and technical data, `http://www.airbus.com/aircraft/support-services/airport-operations-and-technical-data/aircraft-characteristics.html`, accessed: 2018-06-01 (2018).

[118] A. J. Wright, Airbus, Ian Allan Ltd., Shepperton, Surrey, 1984.

[119] Jane's by IHS Markit, Airbus A310, `https://janes.ihs.com/Janes/Display/jau_a005-jau_`, accessed: 2018-06-30 (2018).

[120] M. Kingsley-Jones, J. Moxon, K. O'Toole, P. Lewis, D. Learmount, P. Henley, A320 family, in: Airbus Industries: 25 Flying Years – A Flight International Supplement, Reed Business Information, Ltd, Sutton, Surrey, 1997, pp. 16–18.

[121] Jane's by IHS Markit, Airbus A320, `https://janes.ihs.com/Janes/Display/jawa0416-jawa`, accessed: 2018-05-24 (2018).

[122] Jane's by IHS Markit, Airbus A318, `https://janes.ihs.com/Janes/Display/jawa0417-jawa`, accessed: 2018-06-30 (2018).

[123] Jane's by IHS Markit, Airbus A319, `https://janes.ihs.com/Janes/Display/jawa0418-jawa`, accessed: 2018-06-30 (2018).

[124] Jane's by IHS Markit, Airbus A321, `https://janes.ihs.com/Janes/Display/jawa0419-jawa`, accessed: 2018-06-30 (2018).

[125] Airbus, First A321LR successfully completes maiden flight, `http://www.airbus.com/newsroom/press-releases/en/2018/01/first-a321lr-successfully-completes-maiden-flight.html`, accessed: 2018-06-30 (2018).

[126] J. Flottau, Airbus Launches Long-Range A321neo Version, Aviation Week & Space Technology`http://aviationweek.com/commercial-aviation/airbus-launches-long-range-a321neo-version`. Accessed: 2019-01-22.

[127] P. K. C. Rudolph, High-lift systems on commercial subsonic airliners, Tech. Rep. NASA Contractor Report 4746, National Aeronautics and Space Administration, Ames Research Center, California 94035-1000 (1996).

[128] Airbus, EASA and FAA certify long-range capability for A321neo, `https://www.airbus.com/newsroom/press-releases/en/2018/10/easa-and-faa-certify-long-range-capability-for-a321neo-.html`, accessed: 2019-01-04 (2018).

[129] Airbus, A319neo with CFM LEAP-1A engines wins joint Type Certification from FAA and EASA, `https://www.airbus.com/newsroom/press-releases/en/2018/12/a319neo-with-cfm-leap-1a-engines-wins-joint-type-certification-f.html`, accessed: 2019-01-04 (2018).

[130] M. Kingsley-Jones, Airbus twin still peaking, Flight International (2017) 32–39.

[131] Jane's by IHS Markit, Airbus A330, `https://janes.ihs.com/Janes/Display/jawa0422-jawa`, accessed: 2018-06-30 (2018).

[132] G. Norris, M. Wagner, Airbus A340 and A330, Motorbooks International, St. Paul, MN, USA, 2001.

[133] Airbus, Airport Operations – AutoCAD 3 view aircraft drawings, `http://www.airbus.com/aircraft/support-services/airport-operations-and-technical-data/autocad-3-view-aircraft-drawings.html`, accessed: 2018-05-30 (2018).

[134] Jane's by IHS Markit, Airbus A340, `https://janes.ihs.com/Janes/Display/jawa0421-jawa`, accessed: 2018-06-30 (2018).

[135] U. C. A. Authority, Extended range twin operations, `https://www.caa.co.uk/Commercial-industry/Aircraft/Operations/Navigation-approvals/ETOPS/`, accessed: 2019-01-17 (2015).

[136] A. Today, A340-300 and B777-200ER Current and Residual Values 'On Watch' Status, Aviation Today`http://www.aviationtoday.com/regions/weur/3348.html`. Accessed: 2019-01-17.

[137] J. Flottau, Airbus Bids Adieu to A340, Postpones A350 Delivery, Aviation Week & Space Technology`http://aviationweek.com/awin/airbus-bids-adieu-a340-postpones-a350-delivery`. Accessed: 2019-01-17.

[138] K. Walker, Airbus Secures Saudi Arabian as A330-300 Regional Launch Customer, Aviation Week & Space Technology`http://aviationweek.com/paris-air-show-2015/airbus-secures-saudi-arabian-a330-300-regional-launch-customer`. Accessed: 2019-01-22.

[139] Airbus, A330-800, `https://www.airbus.com/aircraft/passenger-aircraft/a330-family/a330-800.html`, accessed: 2019-01-22 (2019).

[140] Airbus, A330-900, `https://www.airbus.com/aircraft/passenger-aircraft/a330-family/a330-900.html`, accessed: 2019-01-22 (2019).

[141] Airbus Airport Operations, A330neo Airport Operations Brochure – Issue 1 (2016).

[142] D. Kaminski-Morrow, Farnborough: Airbus outlines A330neo engineering demands, FlightGlobal`https://www.flightglobal.com/news/articles/farnborough-airbus-outlines-a330neo-engineering-dem-401664/`. Accessed: 2018-06-30.

[143] Airbus, Airbus A330-900 receives EASA Type Certification, `https://www.airbus.com/newsroom/press-releases/en/2018/09/airbus-a330-900-receives-easa-type-certification.html`, accessed: 2019-01-04 (2018).

[144] FlightGlobal, Airbus A350XWB Aircraft Profile, FlightGlobal`https://www.flightglobal.com/news/articles/airbus-a350xwb-aircraft-profile-217932/`. Accessed: 2019-01-17.

[145] Jane's by IHS Markit, Airbus A350 XWB, `https://janes.ihs.com/Janes/Display/jawaa054-jawa`, accessed: 2018-06-30 (2018).

[146] M. Kingsley-Jones, Airbus confirms switch to A380-style nose for A350 XWB, FlightGlobal`http://www.flightglobal.com/articles/2007/09/21/216949/airbus-confirms-switch-to-a380-style-nose-for-a350-xwb.html`. Accessed: 2019-01-17.

[147] D. Learmount, A350 avionics to expand on A380 systems, FlightGlobal`http://www.flightglobal.com/articles/2007/07/24/215493/a350-avionics-to-expand-on-a380-systems.html`. Accessed: 2019-01-17.

[148] M. Kingsley-Jones, Airbus unveils mock-up of A350 XWB cabin, FlightGlobal`http://www.flightglobal.com/articles/2007/09/28/217395/pictures-airbus-unveils-mock-up-of-a350-xwb-cabin.html`. Accessed: 2019-01-17.

[149] D. Kaminski-Morrow, Picture: First a350-900ulr starts flight-test campaign, FlightGlobal`https://www.flightglobal.com/news/articles/picture-first-a350-900ulr-starts-flight-test-campai-447920/?cmpid=SOC|Twitter|Flightglobal|sf187551548|sf187551548&sfid=701w0000000uP3H#sf187551548`.

[150] Airbus, First Ultra Long Range A350 XWB delivered to Singapore Airlines, `https://www.airbus.com/newsroom/press-releases/en/2018/09/first-ultra-long-range-a350-xwb-delivered-to-singapore-airlines.html`, accessed: 2019-01-04 (2018).

[151] D. Kaminski-Morrow, Picture: Airbus rolls out first a350-900ulr, FlightGlobal`https://www.flightglobal.com/news/articles/picture-airbus-rolls-out-first-a350-900ulr-446286/`.

[152] M. Kingsley-Jones, Airbus opts for larger wing on a350-1000 through trailing edge extension, FlightGlobal`https://www.flightglobal.com/news/articles/airbus-opts-for-larger-wing-on-a350-1000-through-tra-341004/`.

[153] Jane's by IHS Markit, Airbus A380, `https://janes.ihs.com/Janes/Display/jawa5306-jawa`, accessed: 2018-06-30 (2018).

[154] L. Harper, More A380s of interest to IAG but prices 'ridiculous': chief, FlightGlobal`https://www.flightglobal.com/news/articles/more-a380s-of-interest-to-iag-but-prices-ridiculou-446484/`. Accessed: 2019-01-17.

[155] J. Flottau, Report Card: Airbus A380 After Eight Years In Service, Aviation Week & Space Technology`http://aviationweek.com/airbus-a380/report-card-airbus-a380-after-eight-years-service`. Accessed: 2019-01-17.

[156] J. Flottau, Airbus details A380-plus modifications, FlightGlobal`http://aviationweek.com/paris-air-show-2017/airbus-details-a380-plus-modifications`. Accessed: 2018-06-30.

[157] B. N. Nield, An overview of the boeing 777 high lift aerodynamic design, The Aeronautical Journal 99 (989) (1995) 361–371.

[158] G. Norris, Boeing 777 – unveiling a design classic (1990), Aviation Week & Space Technology`http://aviationweek.com/blog/boeing-777-unveiling-design-classic-1990`. Accessed: 2018-07-01.

[159] Bombardier Aerospace Commercial Aircraft Customer Support, Canadair Regional Jet Planning Manual CSP A020 Revision 8, `https://customer.aero.bombardier.com/webd/BAG/CustSite/BRAD/RACSDocument.nsf/51aae8b2b3bfdf6685256c300045ff31/ec63f8639ff3ab9d85257c1500635bd8/$FILE/ATT1ES4H.pdf/CRJ200APMR8.pdf`, accessed: 2019-01-21 (2016).

[160] Bombardier Commercial Aircraft, CRJ Series, `https://commercialaircraft.bombardier.com/themes/bca/pdf/Bombardier_CRJ_Series_Brochure.pdf`, accessed: 2019-01-21 (2017).

[161] D. W. Lim, D. N. Mavris, A design methodology for lifelong aircraft evolution, in: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Vol. 4, Orlando, FL, 2010, pp. 3305–3323.
URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-78649851045{&}partnerID=40{&}md5=5e08e9d84b20ed762aa11aef9b4c76b6`

[162] A. S. J. van Heerden, M. D. Guenov, A. Molina-Cristóbal, A. Riaz, Enhancing the exploration of aircraft changeability during conceptual design, in: 30$^{\text{th}}$ Congress of the International Council of the Aeronautical Sciences, September 25–30, Daejeon, South Korea, 2016.

[163] D. Kaminski-Morrow, A350 stretch would need further engine evolution: Bregier, FlightGlobal`https://www.flightglobal.com/news/articles/a350-stretch-would-need-further-engine-evolution-br-444920/`. Accessed: 2019-01-22.

[164] G. Norris, Boeing Studying Further 777X Stretch, Aviation Week & Space Technology`http://aviationweek.com/shownews/boeing-studying-further-777x-stretch-0`. Accessed: 2019-01-22.

[165] S. Trimble, FARNBOROUGH: NMA development window narrows to six years, FlightGlobal`https://www.flightglobal.com/news/articles/farnborough-nma-development-window-narrows-to-six-y-450239/`. Accessed: 2019-01-22.

[166] R. H. Liebeck, Design of the blended wing body subsonic transport, Journal of Aircraft 41 (1) (2004) 10–25.

[167] D. Scholz, Design aspects of passenger box wing aircraft, in: 3rd Symposium on Collaboration in Aircraft Design, 19–20 September, Linköping, Sweden, 2013.

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