The influence of technology trends on future aircraft architecture

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Abstract

In the last thirty years aircraft performance has experienced diminishing returns in terms of efficiency, on the order of 1% reduction in fuel consumption annually since 2010. Meanwhile, according to projections by Airbus and Boeing, air passenger traffic is expected to increase 3.5-4.6% per annum. ICAO has recommended that overall energy efficiency be improved by 2% annually. The rate of increase in demand and decrease in fuel consumption, raises the question of how this goal can be met. In this paper, engine technology advances are identified as the most significant contributing trend to aircraft performance. These trends are extrapolated in order to analyze the conditions that could lead to a potential break in the dominant aircraft architecture. A hybrid analytical-empirical model for aircraft optimization is used to predict the effects of these technological trends on aircraft design. Four technology scenarios are used to analyze the expected performance increase and expected year of break in architecture, for existing airframes and unconstrained airframe geometry. It is found that for existing airframes performance is expected to increase by 6-38%

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relative to the 737MAX and A320neo within the next 10-14 years, and 17-40% for an unconstrained airframe within the next 20-30 years.

1 Introduction

Civil passenger aircraft have a short commercial history, relative to other modes of transportation. **The first scheduled commercial airline flight took place on 1st January 1914 from St. Petersburg, FL to Tampa, FL, [1] and one of the first recorded international flights was a KLM-operated Amsterdam to Batavia (modern day Jakarta) flight in 1924, taking weeks to complete. Despite these huge advances, it was not until the inception of the Douglas DC-3 that this opened up to a larger commercial market [2].** Airlines such as Imperial Airways in Great Britain and Pan American World Airways in the US started international flights in the 1930s. Imperial airlines carried 23,900 passengers in 1930, its longest route being its London-Cape Town service [3], while the entire US airline industry accounted for approximately 6000 passengers in the same year [4].

Fast forward to 2015 and the number of air passengers in the US has grown to over 800 million [5]. This contrast shows that, despite its relatively short life, air transport has developed immensely. To enable this immense growth air travel has had to become faster, more comfortable, and cheaper for passengers. Although vast amounts of capital have been deployed to develop the air transport system infrastructure, the most important driver of this passenger traffic trend has been the development of economically efficient passenger aircraft [6].

Commercial passenger aviation has an illustrious history, with the civil passenger aircraft or airliner at the center of this development. In modern times, societal needs are rapidly changing in terms of economics and the environment; therefore we ask the question, how will the airliner evolve to meet the needs of a future society? There are four main trends which motivate this question. Firstly, over the last eighty years of commercial passenger aviation there has been a reduction in the variation of aircraft architectures and the emergence of a dominant design. In the early years of commercial aviation, there were substantial variations in aircraft architecture [2]. As time has progressed many architectural options, such as engine location above the wing, have died out leading to a consolidation of aircraft architecture. Associated with this consolidation in architecture is an "S-curve" improvement in aircraft performance, in which we have entered a period of diminishing returns [7]. Incremental improvements in aircraft technologies has driven this trend making it increasingly difficult to provide gains in performance. Marginal improvements are being made in order to reduce operating costs for airlines through increasing reliability, decreasing maintenance costs, and increasing fuel efficiency [8]. It is projected that fuel burn will decrease at an annual rate of 0.96-1.16% until 2050, given various technology and operational scenarios [9]. The third trend is the number of passengers is expected to increase dramatically in the future putting a strain on infrastructure, existing aircraft and the environment. It is projected that there will be 7 billion passengers by 2034, up 112% from 3.3 billion in 2014 [10]. Airbus predicts an annual growth rate of 4.6% over the next 20 years [11], while Boeing expect between 3.5-4.5% annual growth in the next decade [12]. Finally, the ink is still drying on the Paris agreement to keep global average temperature increase to below $2°C$ since pre-industrial levels. Following this, ICAO's Committee on Aviation Environmental Protection (CAEP) have introduced a recommendation for increasing energy efficiency by 2% per year, as a CO_2 efficiency standard for new aircraft [9]. It can be seen that the consolidated aircraft architecture and diminishing improvements in aircraft performance, combined with the increase in passenger traffic demand, are in direct conflict with the environmental goals of the next few decades. This raises the important question of how the current architectural trends might lead to this conflict being resolved in the future. That is, what potential future evolution of the current dominant architecture will enable the future demand to be met while realizing the ambitious environmental goals.

There have been several proposed aircraft architectures which promise increased aircraft performance such as the unducted fan pusher, double bubble, blended wing body and flying wing [13, 14, 15, 16]. These architectures are corner points on the envelope of the architectural design space. If one considers the evolution of architectures as a pathway or trajectory, the historical trajectory has been mapped in [7], and it is possible to conceive of many such potential future trajectories. There are many possible ways that aircraft architecture could change, considering the entire space of possible architectural decisions. Rather than propose new architectures and show the potential benefits, this paper *analyzes the conditions that could trigger a break of the current dominant architecture*. Thus it proposes *possible initial conditions for a new trajectory in the architectural design space*, driven by trends in aircraft technologies, leading to architectural evolution.

A recent trend in civil passenger aircraft is installation of new engines on existing airframes, present in the Airbus "new engine option" (neo) family and the Boeing 737 MAX aircraft family. In the context of this trend, there are two main questions that this paper aims to answer:

1. Given the geometric limitations of the current airframes and advances in aircraft technologies, what is the limit of improvement in aircraft performance?

2. Given the current architecture, allowing for changes in airframe design parameters, and advances in aircraft technologies, what are the performance limits of the current dominant architecture? That is, when can the current dominant architecture be expected to break, given trends in aircraft technologies, where architectural changes occur due to limits in performance of the current architecture?

The subsequent sections, which aim to answer these questions, are organized as follows. In Section 2 we review existing work on aircraft design and optimization, aircraft architectural and performance trends over time, and future aircraft archtectures. Section 3 details trends in aircraft technologies and identifies the most pertinent technology drivers of performance. In Section 4 the method is discussed including a detailed flow chart of the model utilized for the analysis. Section 5 highlights the main results of the analysis for the two main questions asked in this paper, before discussing the results in Section 6, and finally ending with concluding remarks in Section 7.

2 Literature Review

There has been an abundance of work done in the general domain including: the optimization of existing aircraft architectures for maximizing aircraft performance or minimizing environmental impact; examining potential future architectures which have superior performance over the current dominant design; and, extrapolating performance trends in order to predict future aircraft performance. There has been limited work analyzing how the current state of aircraft architecture may evolve over time, continuing to increase performance to meet the goals of a future society. Due to the uncertainty associated with the future of passenger air transportation, there are many potential trajectories in aircraft performance and architecture. While some have postulated what a future air transport system may look like [17, 16, 15, 14], this paper utilizes trends in aircraft technologies to map specific trajectories and identify when the current dominant architecture is likely to break. An examination of the pertinent literature will be presented below.

In aircraft design, the conceptual phase consists of aggregating the design requirements and available technology, culminating in a concept sketch [18, 19]. Raymer [18] describes this process as including a combination of customer requirements, new concept ideas and available technologies;

therefore the decisions are not explicitly stated but rather are reliant on legacy designs and expert knowledge. Torenbeek describes the aircraft architecture or configuration as the general layout, the external shape, dimensions and other relevant characteristics, thus exclude minor decisions such as the layout of the high lift devices [20]. In the conceptual stage of design an aircraft architect must decide on the architecture, which consists of lifting surface arrangement, control surface location, propulsion system selection, payload storage, landing gear and subsystem configuration [21]. According to Howe, several decisions such as the cantilever monoplane wing are static, and therefore the architectural decisions consist of the number of engines and their location, the vertical position of the wing and the configuration of the empennage [22]. More recently computational methods for architecture selection have been developed, including the use of Genetic Algorithms for optimization of small aircraft [23], and probabalistic methods for examining aircraft architecture feasibility [24]. In this context the aircraft architecture is defined as the most important, high-level decisions pertaining to the configuration of the aircraft.

Architectural changes are distinct from incremental changes or modular changes in that they involve reconfiguration of components within a system without necessarily changing the components themselves [25]. For example, two major architectural changes in commercial aircraft were the introduction of the metallic monoplane, and the introduction of the transonic jet aircraft, which were separated by a period of incremental innovation. Gardiner describes the evolution of aircraft architecture in anecdotal form, documenting the major design trajectories in civil aircraft from the 1930s to the 1980s linking these to the major economic climate of each decade. Similarly, Miller and Sawers [2] highlight several key advances, which changed the course the technical development of aircraft from the 1920s to the 1970s, **including the introduction of the metallic monoplane architecture with the Boeing 247 [26], and the production jet airliner, with the De Havilland Comet [27]**. Kellari et al. go one step further and quantify the variation of architectures over time showing the emergence of a dominant architecture [7].

While there is limited literature on the variation of architectures over time, there is an abundance devoted to charting aircraft performance over time, using a variety of different metrics. In the domain of civil aviation, the performance of aircraft is tracked in terms of technical, economic, environmental and operational factors. Aircraft technical performance is typically characterized by payload-range graphs, take-off and landing field lengths, climb rate/angle, and the cruise performance [18, 19, 20] which uses metrics such as cruise speed, specific fuel consumption, and lift-to-drag ratio [28, 29].

Additionally there are many metrics used to characterize aircraft productivity. These include aircraft productivity index [30], utilization per day, average stage-length, load factor, available seat mile and revenue passenger mile [31]. In terms of operational efficiency, airlines typically use total aircraft block hours, daily airborne hours, number of departures per aircraft day, and other similar metrics [32].

While the above are conventionally used in industry, researchers often devise their own metrics to assess the particular field of interest. For instance, Hileman and Katz [33] define a productivity metric to measure the energy required to move a given payload a certain distance, defined as the payload fuel energy efficiency. This metric is chosen due to its ability to incorporate cargo as well as passenger flights in a productivity measure, as well as compare alternative fuels since the cost function is the energy of fuel. Lee et al. [8] and Babikian et al. [34] use an energy intensity metric in statistical and analytical models to examine the influence of aircraft performance on cost from the 1960s until the early 2000s. Lee finds that an annual decline in air transport energy intensity of 1.2%-2.2% is not sufficient to offset the increase of 4%-6% in passenger air travel, therefore emissions are expected to increase. By contrast, Dallara et al. [35] have devised a metric known as average temperature response, to quantify the lifetime global mean temperature change caused by aircraft operations. Antoine [36] and Schwartz [37] use this metric to analyze the impact of different aircraft designs on global climate finding that a 30% reduction in global warming impacts is attainable by changing aircraft operating conditions. While the aircraft design is varied in terms of design parameters, the aircraft architecture remains the same in this analysis.

As well as charting historical trends, there is considerable research devoted to the optimization of point designs in the architectural space. This can be largely split into two major fields of research: firstly the optimization of design variables for the current dominant architecture to minimize fuel burn, environmental impact in terms of emissions or noise, or operating costs; secondly the analysis of alternative architectures to the dominant architecture, in order to demonstrate superior performance along similar dimensions. The optimization of the dominant architecture is usually carried out with the use of multidisciplinary design optimization (MDO), changing the design variables to maximize or minimize a specific objective [8, 38, 36, 39]. For example, Bower et al. use a MDO methodology to design a single aisle aircraft to minimize direct operating costs (DOC), CO_2 emissions and NO_x emissions [40]. They find a Pareto frontier on which these three objectives are traded in the context of the dominant architecture, with CO_2 and DOC being very correlated. Similarly Antoine et al. [36] developed a design tool using a MDO approach to quantify tradeoffs between noise performance, DOC, and emission performance. This was carried out by modifying design variables within the dominant architecture, showing that modification of the design parameters can only go so far in order to increase performance, without using abatement technologies. They cite that any such design tool is heavily reliant on verification and validation since there is inherent uncertainty in the model. Raymer [41] evaluates multiple MDO methods in the context of four different architectures including a commercial airliner. He demonstrates how optimization improves the weight and cost of an such design concepts by approximately 2-10% through tweaking design variables. Although, within the context of a single architecture, this method generally demonstrates increase in performance compared to traditional design methods, it is not able to optimize across the architectural decision space.

In addition to the dominant architecture, optimization has been carried out for other point designs in the architectural space, representing potential future architectures. An often cited way to increase the lift-to-drag ratio of passenger aircraft is to shift to a blended-wing body (BWB) or flying wing architecture [13]. According to a study by Cranfield University a BWB architecture could increase lift-to-drag ratio by 15% resulting in a 17% reduction in fuel burn per unit of payload-range [42]. In addition to this, such architectures provide other benefits, such as enabling alternative propulsion systems. Green carried out studies of BWB and flying wing architectures with unducted fan engines, demonstrating a projected fuel burn per unit payload-range of 50% lower than current passenger aircraft [43]. Similarly NASA have carried out studies of two potential future architectures for the 2030-2035 time period, one defined as a “double-bubble” architecture (the D-8 Series), and the other defined as a “hybrid wing body” architecture (the H-3 Series) [44]. The D-8 demonstrates an reduction in fuel burn of 70%, reduction in noise of 60dB, and a reduction in NO_x emissions of 87% relative to today’s baseline technology. Although there is a clear outline of the technology requirements to reach these performance improvements, there is a gap in how the architecture will evolve from the baseline dominant architecture to this future double-bubble architecture [44]. **It is also worth noting that there are considerable obstacles in obtaining airworthiness certification for these architectures, for example the emergency evacuation requirement in the case of the BWB.**

While there has been much research dedicated to the design and optimization of singular point designs, there has been significantly less work analyzing the effect of architectural decisions. Green documents the potential of new technologies, for example contra-rotating engine technology, and aircraft architectures such as the blended-wing body, concluding that substantial reduction in CO2 emission will require radical changes to aircraft design in particular deviation away from the dominant swept-wing architecture [16]. That being said there has been little research dedicated to examining the path that may take us from this current architecture to potential future architectures with superior performance. Despite the advantages of such future architectures, the apparent architectural "lock-in" of the current dominant architecture is a major barrier for the industry to overcome and there has been significantly less effort devoted to understanding the trajectories that could lead to something such as the D-8 or H-3.

3 Technology trends

There is a wide body of literature around aircraft technology selection under uncertainty, in order to mitigate the risks associated with their long development cycle [45, 46]. The influence of such technologies on aircraft architecture has not been as widely examined. It has been shown that engine architecture is a major driver in the vector input for aircraft architecture. The most important engine technology trends within the context of the turbofan and geared turbfan architecture are identified and analyzed. The identified trends are increasing bypass ratio, increasing individual component efficiency, and increasing turbine inlet temperature along with increasing overall pressure ratio. These factors are quantified and extrapolated in time in order to predict the innovation in these technologies in the future.

These advances in these engine technologies are constrained by a number of factors including: material thermal properties, specifically the low pressure turbine materials which limit the turbine inlet temperature [47]; environmental regulation of emissions through standards for engine certification [48, 49]; increase in mass and associated with larger fan diameters [43]; aerodynamic issues such as flow separation due to stall or fan surge [47]; and geometric constraints of the dominant architecture which emplys under-wing engines. This paper assumes that research and development of engine technologies can overcome the first four of these. Hence this assumes that the geometry of the dominant architecture is the limiting constraint in improving aircraft performance through advances in engine technologies.

For example, the 737-MAX family is the latest in Boeing's single-aisle aircraft, and is essentially a re-engined version of the 737-Next-Generation (737NG) family, with minor changes to the wing tips, as shown in Appendix C [50]. The main design requirement which restricts the size of an under-wing engine is the ground clearance requirement.

Decision	Option
Wing Vertical Location	Low Wing
Wing Shape	Swept Back
Wing Passive Control Shape	Dihedral
Engine Type	Turbofan
Number of Engines	Two
Engine Location	Under-wing
Pitch Stabilizer Vertical Location	Fuselage (Inverted T)
Pitch Stabilizer Shape	Swept Back
Landing Gear Arrangement	Tricycle
Location of Stowed Landing Gear	Wing-Fuselage

Table 1: The dominant aircraft architecture enumerated using decision-options.

A comparison of the two engines is provided in Appendix C for these two iterations of this aircraft showing an increase in engine diameter. It can be seen from this table that there is a substantial increase in bypass ratio associated with technological innovations in materials and structures, enabling larger fan diameters without harming performance. Figure 9 shows how the ground clearance limits have been reduced with the inception of new engine technology. As these engine technological trends continue one expects that the ground clearance limits will be reached.

This analysis of technology trends reinforces the notion that aircraft propulsion will be a significant driver for improvements in performance in the future. Based on this it is reasonable to believe that future developments in aircraft propulsion may lead to the breaking of the current dominant aircraft architecture. Specifically the question being asked here is, when does the trend in increasing bypass ratio break the architecture? To answer this question it is necessary to model the aircraft design and performance, the engine design and performance and the interactions between these two in the context of the dominant architecture.

4 Method

It is necessary to use a model to compute aircraft geometry and performance, taking as inputs the mission profile and available technologies, in the context of the dominant architecture. The term "dominant architecture" or "dominant design" in the context of this paper refers to the architecture exhibited in Table 1, enumerated as decision-options.

The performance metric used in the following analysis is the aircraft passenger carrying efficiency. This metric is defined as the available seat kilometer per kilogram of fuel carried, similar to the payload fuel energy efficiency metric defined by Hileman and Katz [33]. Given that available seat kilometer is constant for a particular aircraft design, this metric quantifies aircraft performance as the block fuel required for a given mission.

For a civil passenger aircraft displaying the dominant architecture, given a vector of inputs for mission specification and initial aircraft definition parameters, $\mathbf{x}$, the model, F, sizes the aircraft in terms of weight, computes the aircraft drag, optimizes for engine and landing gear integration while maintaining stability, and outputs aircraft and engine geometry and performance, $\mathbf{y}$, that is $\mathbf{y} = F(\mathbf{x})$. A hybrid analytical-empirical model is utilized to carry out the analysis in this paper. The model consists of four main modules: an airframe sizing module, an engine sizing module, an integration module, and a performance calculation module. Each of these consist of multiple functions interacting to carry out a discrete optimization of the aircraft geometry for maximum performance. The assumptions and methods used in the model will be briefly described here but we refer the reader to [7] for full mathematical details of the model and its verification.

4.1 Initial airframe-engine geometry & weight estimation

For a given mission profile and technology inputs shown in Appendix A, the airframe and engine are initially sized based on established methods from conceptual aircraft design literature [18, 19, 21, 20, 22, 28]. The airframe sizing uses several empirical formulae as well as analytical methods. Meanwhile a one dimensional analytical model for a real turbofan engine is used to size the engine in terms of geometry, weight and performance.

The operating conditions are calculated for each of the mission profile segments using standard atmospheric (ISA) data. Subsequently the aircraft empty weight and fuel weight are computed using the weight fraction method based on assumptions of a weight fraction for each segment of the mission [18]. Following this the thrust-to-weight ratio and wing loading are determined for each segment of the mission profile by assuming a lift-to-drag ratio based on existing aircraft. The lowest value of wing loading is then used to initially size the wing area and hence the wing geometry by making several assumptions including sweep angle, aspect ratio and taper ratio, based on legacy aircraft.

From these values the geometry of the airframe can then be determined. This method incorporates assumptions for certain parameters, such as the fuselage fineness ratio and tail volume coefficients. This widely employed in industry and academia for high-level aircraft design and is therefore considered valid within the context of the dominant architecture [18, 19]. Given the major geometrical elements have now been defined, the mass of the aircraft can be refined based on a similar weight fraction method utilizing more details specific to this particular aircraft geometry.

The engine is initially sized based on the real turbofan analytical model which idealizes a turbofan as shown in Figure 1. This turbofan engine model takes as inputs the aircraft thrust requirement and the engine technology parameters highlighted in Appendix A. It utilizes an approach derived from first principles, based on 1D fluid flows, to determine the engine size and performance such as specific fuel consumption. This method is based on well-known analytical equations for turbofan analysis [47] and is powerful due its ability to reliably predict performance for a wide range of inputs.

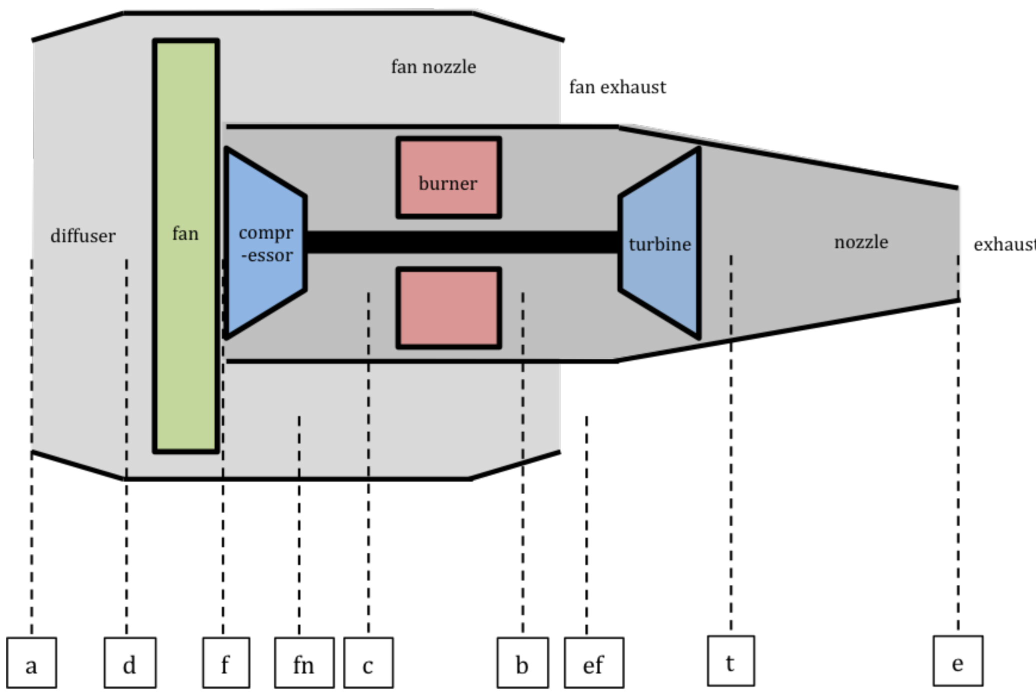


Figure 1: A schematic diagram of the idealized turbofan engine used in this model.

Consequently the landing gear and tire loads are determined, based on the worst-case landing scenarios. A statistical method based on weight fractions with respect to the maximum takeoff weight is then utilized to compute the weights of the major components [19]. Using these weights the center of gravity of the aircraft is initially estimated using assumptions for the locations of certain components such as the leading edge of the wing and the landing gear. In parallel the aerodynamic performance of the aircraft is computed. This involves using an empirical method to determine the aircraft lift-curve with and without high lift devices, and the "drag buildup" and Oswald span efficiency methods to determine parasitic and lift-induced drag [18].

The next step in the process is to use longitudinal static stability equations to calculate the neutral point of the aircraft. An iterative method is used to position the aircraft components such that the conditions for longitudinal static stability are met. This method requires re-calculation of the center of gravity of the aircraft for each iteration due to the relocation of components; this iteration continues until the design has converged on component locations which satisfy the criteria for longitudinal static stability. Lateral stability has not been accounted for since it would not have a large bearing on the aircraft geometry and the performance metric of interest. Similarly it is assumed that the volume coefficient method used to size the aircraft vertical tail implicitly accounts for yaw stability.

At this point we have initial estimates of the aircraft geometry, mass, center of gravity, aerodynamic performance, fuel consumption, thrust to weight ratio, lift to drag ratio, etc. at different segments of the design mission. In order to analyze the effects of the engine, and advances in engine technology, on the aircraft design parameters and architecture performance, it is necessary to capture the interactions between the engine and airframe. Since the engine location in the dominant architecture is under the wing there are interactions between the engine, the wing, the landing gear and the fuselage. Capturing these interactions is required to optimize the aircraft design for increased performance. The aircraft performance is therefore maximized subject to geometric constraints, architecture constraints, physics constraints and technology constraints.

5 Results

5.1 Limits of dominant architecture within the geometry constraints of existing aircraft

The most recent trend in civil passenger airlines, particularly in the single aisle market, is to re-engine existing aircraft, with the A320neo and the 737MAX leading the way. In response to the threat of new entrants, such as Bombardier, Airbus and Boeing decided to re-engine these aircraft rather than design new aircraft from scratch [51]. This re-engining paradigm assumes that airframe design parameters remain constant, with the exception of reinforcing structures within the existing geometry to handle any increased loads due to the new engine and new wing tip devices. This trend has taken off since the development of a completely new aircraft is associated with high costs and a long lead time, therefore in an uncertain market post-2008 aircraft manufacturers opted for this less risky strategic choice.

The analysis in this section involves a *constant aircraft geometry* taken from existing aircraft, coupled with the engine model, to determine the limits of existing designs. The engine model has been verified with existing aircraft with a mean error of approximately 5% and standard deviation of 7%. The focus of the analysis is on single-aisle aircraft which are more constrained in terms of geometry, hence the 737 and the A320 were selected. In terms of engine technology, four separate scenarios are analyzed for each of these families corresponding to the major trends identified in Section 3. These scenarios are as follows:

1. Baseline scenario: Technologies related to increasing bypass ratio are developed while component efficiencies, turbine inlet temperature, and overall pressure ratio remain at today's level of progress
2. Component efficiency increase: Bypass ratio increases along with improvements in component efficiency, at constant turbine inlet temperature and overall pressure ratio.
3. Turbine inlet temperature and overall pressure ratio increase: Bypass ratio increases along with improvements in turbine inlet temperature and overall pressure ratio, at constant component efficiencies.
4. All major technologies advance: Bypass ratio, component efficiencies, turbine inlet temperature and overall pressure ratio all increase to their practical maximum levels.

These scenarios are used in the analysis throughout this section. The effect of improving various technologies are considered separately in order to segregate the effect of each on the overall performance. The parallel to this in the real world is the allocation of limited R&D funds by manufacturers to improve a given technology.

5.1.1 Constant geometry analysis of 737 and A320: four technology scenarios

The engine ground clearance constraints can be seen in Figure 10 and 11 with detailed geometry presented on the right of the figures. Although this varies depending on the reference cited, according to Roskam [19], the requirement for engine ground clearance is the angle subtended between the line from a 6inch buffer from the nacelle boundary to the landing gear, and the horizontal, $\phi \geq 5°$. For the 737 this is when $x = 0.172m$. Using simple trigonometry it can be calculated that, given $z = 1.97m$, the minimum ground clearance which satisfies the above requirement is $y = x + 0.153 = 0.172 + 0.153 = 0.325m$. Given that the current ground clearance is $0.43m$, there is still room to upgrade the current engines if desired, to a maximum fan diameter of 1.87m. For the A320 this is 2.12m. Using this limit in conjunction with the engine model, it is possible to determine at what point each particular aircraft design will no longer benefit from incremental engine improvements.

The following analysis was run with engine design requirements for a 737-800 and an A320-200, keeping all engine input variables constant, while varying the bypass ratio. The following section will detail the intermediate results for the 737 only. The A320 results followed a similar trend however due to space limitations only the final results for this aircraft will be included at the end of this section.

The results from scenario 1 are shown in Figure 2. The nacelle (and fan) diameter has been assumed to dictate the geometric constraint, along with confidence bounds to account for any errors in the model. Hence shown on each of the graphs is an expected estimate and an expected true value, which includes the model bias.

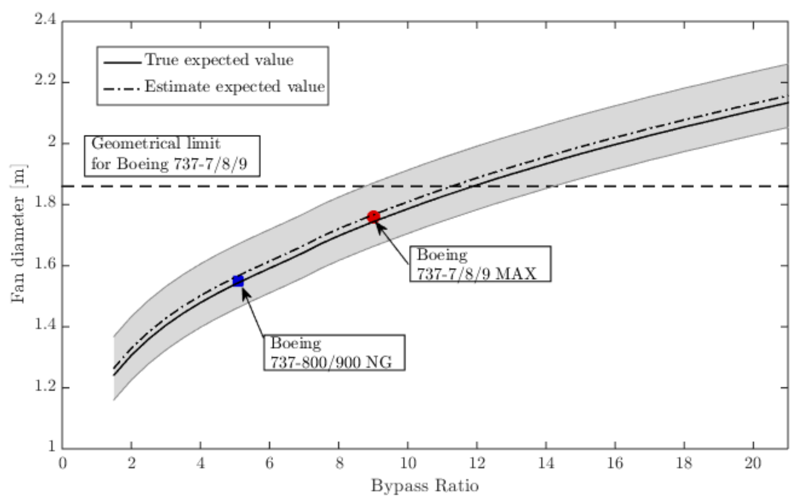


Figure 2: Variation of fan diameter with bypass ratio for the Boeing 737-7/8/9.

From Figure 2, it can be seen that for the given geometric constraint requirements we can say with 95% confidence that a bypass ratio between 9 and 14 would be the maximum permissible for the 737 in scenario 1. The true expected value is approximately 11, assuming normally distributed model error. Beyond these values the maximum possible fan diameter would be reached and the ground clearance criteria violated due to an increase in the fan diameter.

In terms of performance, the model outputs results for SFC and engine weight, which are traded off as bypass ratio increases since SFC decreases but engine weight increases. These interactions need to be captured to determine whether it is beneficial to continue with this trend of increasing bypass ratio. As bypass ratio increases there is a conflict as increasing engine weight contributes to decreasing aircraft performance and decreasing SFC contributes to increasing aircraft performance (decreasing mission block fuel).

The range of feasible maximum bypass ratios is computed from the estimated fan diameter and ground clearance requirement. The true expected value of bypass ratio of 11 results in an expected decrease in required fuel for the mission of approximately 1395 kg from the 737MAX to the 737 with a maximum possible bypass ratio turbofan and 3766kg from the 737NG. This corresponds to an expected decrease in block fuel weight of 8.8% versus the 737MAX and a decrease of 20.6% versus the 737NG, corresponding to a increase in aircraft performance of 9.7% and 25.9% respectively for the design mission . These results are highlighted in Table 2 and 3.

Hence, given current airframes, there is still some room for improvement in performance assuming that engine technologies can advance to produce bypass ratios in this range. Realistically there will be further losses due to unaccounted for 3D effects, such as weight increases due to cooling systems, which are not accounted for in the engine model; therefore 9.7% would be an optimistic value for the true expected value of performance increase. Furthermore production of NO_x has a minimum point as overall pressure ratio increases, and any regulations on this emission could decrease the potential gains in performance. A major assumption of this analysis enabling overall pressure ratio (OPR) and turbine inlet temperature (TIT) to increase is the development of low NO_x combustors.

In addition to increasing bypass ratios, other engine technologies could be improved, as described in the remaining three technology scenarios.

	Technology scenario	Bypass ratio			SFC $\left[\frac{lbm}{lbf \cdot hr}\right]$			Engine Weight [kg]			Mission Fuel Weight [kg]			Fuel Weight Decrease vs. 737MAX [%]		
		Lower	Upper	EV	Lower	Upper	EV	Lower	Upper	EV	Lower	Upper	EV	Lower	Upper	EV
737 airframe	1. Baseline technology	9	14	11	0.465	0.398	0.434	3,157	3,808	3,368	15,012	13,491	14,480	5.4	15.0	8.8
	2. Component efficiency increase	12	17	15	0.379	0.333	0.350	3,199	3,716	3,520	12,934	11,810	12,167	18.5	25.6	23.4
	3. Turbine inlet temperature increase	11	16	14	0.422	0.367	0.387	3,424	4,064	3,787	14,154	12,748	13,186	10.8	19.7	16.9
	4. All technologies improve	14	19	17	0.346	0.308	0.322	3,368	3,834	3,657	12,135	11,200	11,500	23.6	29.5	27.6
A320 airframe	1. Baseline technology	9	16	12	0.465	0.378	0.421	3,270	4,178	3,691	13,837	12,057	12,940	-0.1	12.0	5.5
	2. Component efficiency increase	12	20	16	0.379	0.313	0.342	3,313	4,132	3,750	11,831	10,513	11,081	13.6	23.3	19.1
	3. Turbine inlet temperature increase	11	18	15	0.422	0.350	0.377	3,546	4,357	4,033	12,916	11,444	11,976	5.7	16.5	12.6
	4. All technologies improve	14	21	18	0.346	0.296	0.315	3,488	4,146	3,881	11,124	10,128	10,500	18.8	26.1	23.3

Table 2: Results of main analysis of four technology scenarios for the 737 and A320 airframes.

The analysis is carried out for the four technology scenarios, with results shown in Table 2 and

Technology scenario	Performance increase vs. 737MAX			Performance increase vs. A320neo		
	Lower	Upper	Expected Value	Lower	Upper	Expected Value
1. Baseline technology	5.7	17.7	9.7	-0.1	13.6	5.8
2. Component efficiency increase	22.7	34.4	30.5	15.7	30.4	23.6
3. Turbine inlet temperature increase	12.1	24.5	20.3	6.0	19.8	14.4
4. All technologies improve	30.9	41.8	38.1	23.2	35.3	30.4

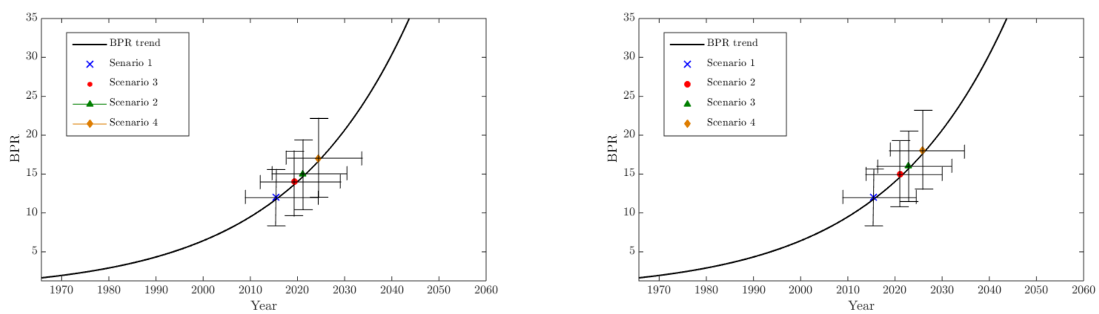
Table 3: Aircraft performance results of four technology scnearios for the 737 and A320 airframes.

Table 3. From these analyses it is clear that within the limits of the current airframes there is room for further improvement in terms of substituting turbofan engines with incremental increases in performance. For the 737, the expected values of increase in performance for scenarios 1-4 are 9.7%, 30.5%, 20.3%, and 38.1% respectively with the upper and lower bounds of the 95% confidence interval shown in the table. These are enabled by accommodating, within the geometrical constraints, turbofan engines with expected bypass ratios of 11, 15, 14, and 17 respectively for each of the four technology scenarios. The improvement in performance for the A320 for scenarios 1-4 are 5.8%, 23.6%, 14.4%, and 30.4% respectively. These are associated with increasing th BPR from its current value of 11 to 12, 16, 15, and 18 for each of the four scenarios respectively, to fully utilize the available aircraft geometry within the constraints of the system.

Although performance improvements are probable, it can be observed that the lower bound of the maximum feasible bypass ratio for this airframe is 9, which happens to correspond to the CFM LEAP 1B engine of the 737-7/8/9 MAX, as seen in Table 10. That is to say there is a small possibility that the fan diameter and hence the bypass ratio limits have already been reached for current engine technology. Taking the baseline technology level for component efficiency and turbine inlet temperature, if fan blade materials and structures were advanced enough we would expect a bypass ratio engine of approximately 11 to be the maximum possible for the current airframe, which corresponds to an increase of 9.7% from the performance of the 737-MAX.

The results that follow the baseline technology analysis, namely increases in component efficiency and TIT & OPR, serve to show the impact of other possible improvements in engine technology. As mentioned in Section 3, these technology trends are considered to be the most likely to be seen in turbofan engines in the near future. The results of improvements along these two dimensions are done independently based on the forecasted values. It can be seen that improvements in both of these independently tend to decrease the fan diameter, therefore enabling possible increases in performance for the given geometric constraints. Note that another technological innovation which has not been included explicitly in this analysis is the inception of a gear to power the fan. The use of geared turbofan has been allowed in the model by setting the range of possible fan pressure ratios and optimizing despite any mismatch in turbine and fan speeds. Since the weight would change due to addition of a gear it is assumed that the decrease in size of the turbine would offset this.

It is posssible to forecast an expected value for the year in which an airframe will no longer be able to increase in performance, based on a forecast of the engine technology advances. The limit in performance is driven by the constraints of an under-wing engine in the contxt of the dominant architecture. A forecast of engine technology advances has been examined in [7]. In this paper these advances are imlicit in a graph of bypass ratio trends against time. The forecast for the limit of each technology scenario is detailed in Figure 3, showing the expected year of architecture break with 85% confidence bounds.



(a) 737 airframe

(b) A320 airframe

Figure 3: Forecast of expected values of BPR for the four technology scenarios.

5.2 Limits of dominant architecture with dynamic aiframe geometry

The analysis in the previous section took existing airframe geometries as a constraint, to quantify the possible performance improvements of current single-aisle aircraft. The purpose of this was to use “real world” constraints to predict when the current trend of re-engining an existing airframe will no longer be possible for performance increases due to geometric constraints of the dominant architecture within the context of these airframes. This next section will take the analysis one step further, removing the constraint of a constant airframe. This will thus relax the design variables for the airframe, remaining within the bounds of the dominant architecture, but unconstrained by the previous limits of airframe geometry. The purpose of this is to analyze, when the dominant architecture could potentially break. That is, examining trends in turbofan engine technologies, at what point will aircraft performance no longer increase, therefore potentially requiring architectural exploration. It is worth noting that this analysis does not account for potential aircraft development times.

As has been mentioned previously, the major trends in turbofan technology are increasing bypass ratio, increasing component efficiency, and increasing turbine inlet temperature along with overall pressure ratio. These tend to result in the fan diameter of the turbofan increasing, and therefore an engine which requires more space underneath the wing for installation. As the ground clearance requirements of the current airframes are approaching their limits, there are several design parameters which can be modified to accommodate larger engine diameters. Within the confines of the dominant architecture, these include:

1. Increase the landing gear length
2. Increase the distance of the engine from the centerline
3. Increase the landing gear track
4. Reducing the engine diameter through engine core technology advances
5. Increase the wing dihedral
6. Reducing the nacelle thickness.

Alternative options such as changing the engine architecture, relocating the engine, or relocating the wing for example to a high-wing configuration, would constitute a *change in architecture* and are therefore not included as options in this analysis. Of the design parameter changes above, all are considered in the model, apart from numbers 5 and 6. The reason that it may not be desirable to increase the wing dihedral is because this would create an aircraft which would be too laterally stable and thus unable to maneuver. Reducing the nacelle thickness has not been explicitly included as part of the analysis, since it is already assumed to be at the lower bound of thickness in the model, therefore any further change would be negligible. The other four possible design variable changes, are highly connected to each other, and to other design variables, therefore changing each one has a large change propagation within the design of the system [52]. These highly non-linear relationships are difficult to predict and therefore are included in a brute force discrete optimization of the airframe-engine interaction. Note that airframe trends such as increasing specific strength of materials for the landing gear for example are not explicitly accounted for in this analysis in order to bound the scope on engine technologies as the driver for performance improvements.

The same technology scenarios to those presented in the previous section will be used in this one. These scenarios will be analyzed in the sections below, allowing the aforementioned hypotheses to be tested. The aircraft analyzed in this section have a similar mission profile to a typical single-aisle aircraft such as the 737 or A320 and are detailed in Appendix D. In the following analysis, each of the scenarios is compared to the state of technology today to measure the potential improvements.

5.2.1 Scenario 1: Bypass ratio increase with baseline technology

This scenario assumes that only the technologies related to increasing the bypass ratio of the turbofan engine will improve, with all other technologies remaining at the baseline level.

The changes in design parameters to accommodate this scenario of engine technology improvement can be seen in Figure 4. It can be seen that three of the design parameter modifications mentioned in the previous section are occurring, that is increase in landing gear length, landing gear track and distance of the engine from the centerline. The engine diameter can be seen to be increasing since BPR is increasing without any core technologies being improved.

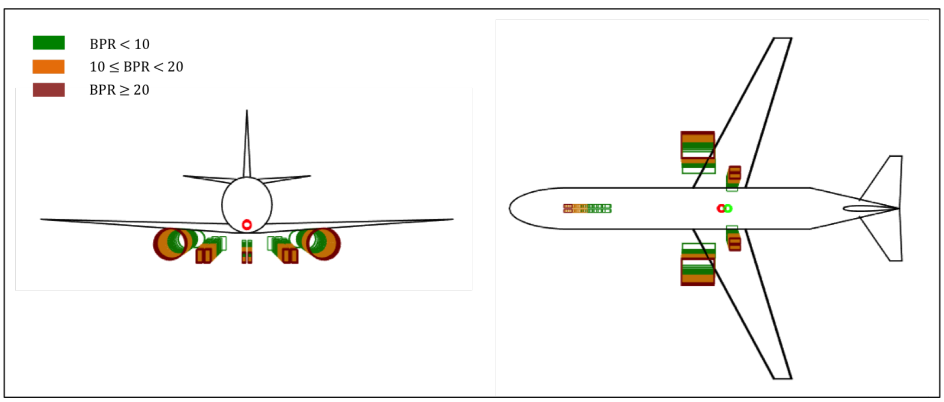
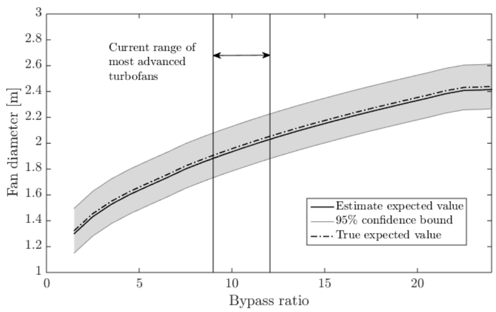
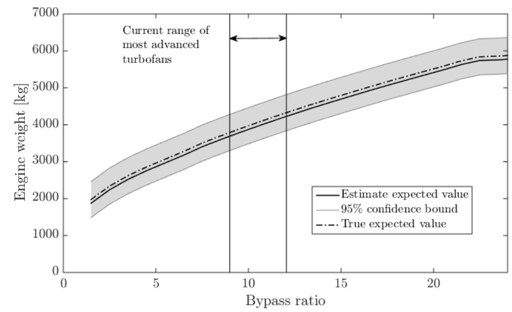


Figure 4: The evolution of aircraft design parameters as BPR increases in scenario 1.

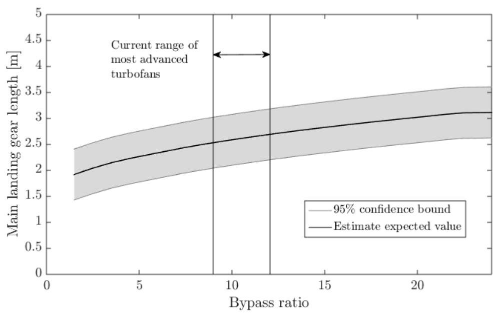
The aforementioned constituents of aircraft performance including SFC, lift-to-drag ratio, and aircraft empty weight (or final mission aircraft weight) change with increasing bypass ratio. The SFC is directly affected by this increase in bypass ratio, however the high-level trends in lift-to-drag ratio and aircraft weight are driven by aircraft design parameters, namely the engine diameter and weight, and the landing gear length and weight. That is, as BPR increases engine diameter increases, therefore drag and empty aircraft weight tend to increase. As landing gear length increases, the landing gear weight tends to increase, leading to an increase in empty aircraft weight. The trends in aircraft design parameters can be seen in Figure 5. On these graphs the estimate expected value is adjusted for potential model bias, producing the true expected value along with 95% confidence bounds.



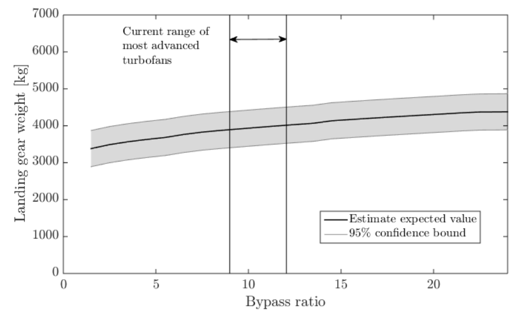
(a) Engine fan diameter



(b) Engine weight



(c) Main landing gear length



(d) Total landing gear weight

Figure 5: Variation of aircraft design parameters as BPR increases for technology scenario 1.

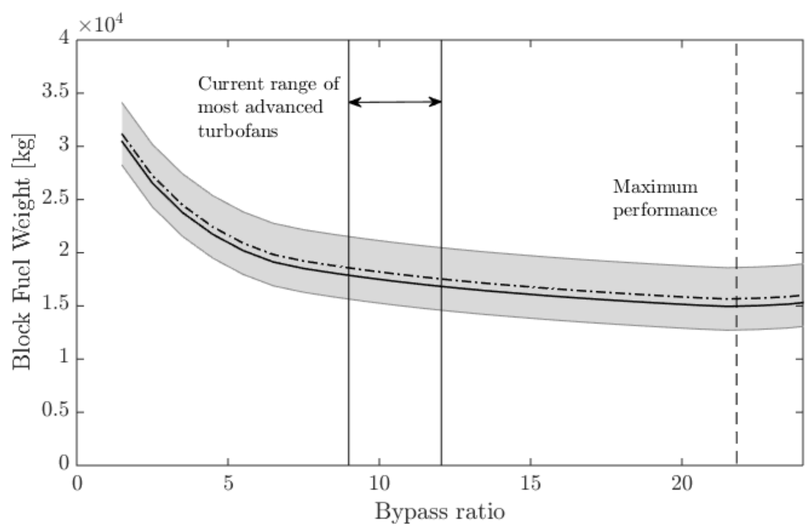


Figure 6: Aircraft performance against bypass ratio for technology scenario 1 for unconstrained aircraft geometry.

Based on the values calculated for this scenario it is possible to use the BPR forecast to estimate when this maximum performance will occur. It is assumed that at this point in time no further performance improvements will be possible based on the engine technology assumptions of this scenario, therefore requiring architectural exploration to further increase performance. The results of this projection are presented in Figure 7, including 85% confidence bounds. It can be seen that two models are shown on the graph, based on different data sets. For the purpose of this analysis the model based on the single-aisle data set is used. In such a model there is a large amount of uncertainty, as can be seen by the large bounds in this graph. Typically a single standard deviation is used to bound the values in such problems to give more meaningful results. These are compiled in Table 4.

This shows that the expected value in technology scenario 1 for the year in which performance will stop increasing is 2030 with a single standard deviation confidence bound of [2025, 2035]. Given that it is expected that the architecture will no longer be able to improve in performance, this is assumed to be the year when the current dominant architecture will break given the assumptions of this scenario.

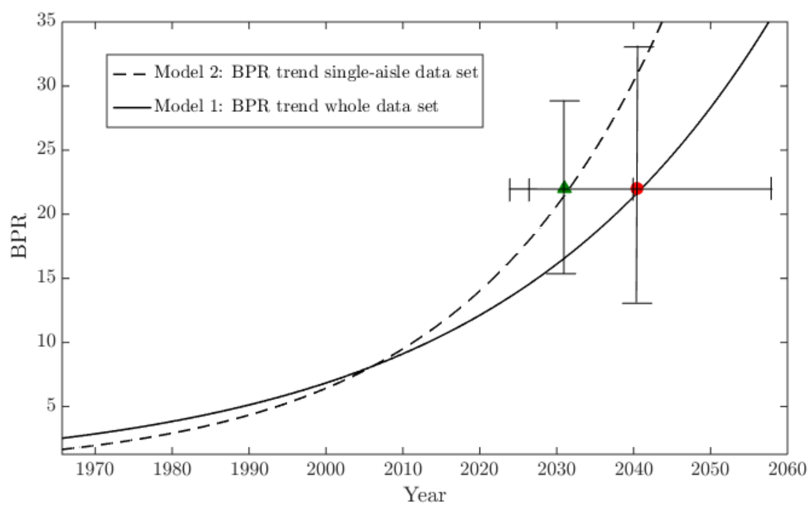


Figure 7: Two forecast models of BPR against year for scenario 1.

	85% confidence			68% confidence		
	Lower	Upper	EV	Lower	Upper	EV
Year of architecture break	2023	2039	2030	2025	2035	2030

Table 4: Expected values for architecture break year for technology scenario 1.

5.2.2 Technology scenarios 2 to 4: unconstrained geometry

The analysis carried out for technology scenario 1 was repeated for the remaining three technology scenarios. That is, the maximum possible improvement in aircraft performance was found given improvements in engine technology formalized in the remaining three technology scenarios, subject to the geometric constraints of the dominant architecture. Since the forecast of engine technolgies and the aircraft physical model contain uncertainties, these have been captured using confidence bounds.

Under these technology scenarios, a forecast of the break in the dominant architecture is computed as in Section 5.2.1. The model of expected values of bypass ratio over time is used, which implicitly accounts for technology advances, including overall pressure ratio, turbine inlet temperature, and component efficiencies. The results of these analyses can be seen in Table 5.

	Year of architecture break					
	85% confidence			68% confidence		
	Lower	Upper	EV	Lower	Upper	EV
Scenario 2	2030	2047	2037	2032	2043	2037
Scenario 3	2026	2042	2034	2029	2039	2034
Scenario 4	2032	2048	2039	2034	2044	2039

Table 5: Expected values for architecture break for technology scenario 2.

6 Discussion of results

The reason that these two analyses have been carried out separately is to analyze two possible situations. The first analysis corresponds to the potential decision of manufacturers to continue the current trend of simply installing new engines on existing airframes. The second analysis corresponds to the potential decision of a manufacturer to develop a new aircraft with the dominant architecture. These two potential decisions encompass the possible trajectories which lead to the current architecture remaining dominant. Given that it has been identified that engine technology and engine architecture are the major drivers for aircraft architecture, engine technology advances have been the forcing functions in these analysis.

The purpose of using separate technology scenarios is to highlight that different advances in technology lead to different outcomes; although the costs of these advances have not been considered, manufacturers may use a similar analysis to try to prioritize partnerships and R&D spending.For example scenario 2 involves improvements in technologies enabling larger bypass ratios and higher component efficiencies, which represents a scenario in which a manufacturer chooses to focus its funding on research towards improving these. Although costs of technology improvements are not explicitly considered in this analysis, examining these trends separately is a proxy for this. Additionally this enables us to isolate the extent to which each of these trends drives aircraft performance, changes in geometry of the dominant architecture and architecture disruption. Consequently, identifying and extrapolating trends in engine technology and examining when the aircraft performance will reach its maximum, enables a prediction of when we might expect the current dominant architecture to break.

The improvements in engine technology can not be taken for granted since they require substantial amounts of time and money to be spent on research and development, which may not be economically feasible for manufacturers. Furthermore more components increase the complexity which could have an effect on engine reliability and direct operating costs. Considering time, cost and complexity, further advances in these technologies yield diminishing returns in terms of performance. That is, at some point the economics of a marginal improvement in bypass ratio, component efficiency, turbine inlet temperature, or a geared turbofan may be substantially less than their associated marginal cost in development and operations.

The second analysis allows the design parameters of the dominant architecture to vary, that is, an unconstrained geometry for a given mission. The same four technology scenarios are analyzed for the unconstrained geometry case in the context of the dominant architecture. To summarize these results, it is shown that in scenario 1 we can expect a performance increase of 17.1% by 2035; in scenario 2 the expected value of performance improvement is 32.4% by 2043; in scenario 3 the performance increase is expected to be 19.6% by 2039; and finally in scenario 4 the performance is expected to increase by 39.9% by 2045.

Note that the baseline for improvement in the constrained geometry analysis is existing aircraft, which are not optimized for the most state-of-the-art technology. In the unconstrained geometry analysis the baseline for measuring the performance improvement is an aircraft optimized for current technology. This results in a baseline aircraft with higher performance for the second analysis versus the first analysis; therefore it is not fair to compare the values of existing airframes to the values in this second analysis. While comparisons between performance improvements are not comparable across aircraft it is easy to compare the results across the four scenarios for each aircraft case. Nevertheless it is possible to compare the architecture break point across the aircraft. This shows us that the A320 architecture will break later than the 737 which is expected due to its longer landing gear and therefore larger area for engine placement under the wing. Furthermore allowing new aircraft to be build by varying the geometry of the dominant architecture naturally allows this architecture to persist for longer than existing airframes.

The results of this analysis can be compared with existing literature. Mentioned in scenario 4 of the second analysis are results from Czech [53] and Ciepluch [54], which have predicted that beyond a BPR of 25-30 an unducted fan is more beneficial than a turbofan or geared turbofan architecture. This coincides with the predictions of these results that an architectural change will be necessary to improve aircraft performance beyond a BPR of 22-30 depending on the technology scenario.

It is well documented that aircraft development requires long lead times on the order of a decade [55]. When this is taken into account it is evident that if for example maximum aircraft performance is expected to occur in 2035, a manufacturer would have to begin the development process around 2025. When an aircraft in a given class requires replacing, the manufacturer must decide whether to modularly innovate by simply installing new engines and other small add-ons, incrementally innovate by designing a new aircraft with the same architecture and small improvements, or architecturally innovate. They must decide whether a potential performance improvement is worth the associated cost. This means that even though an incremental improvement may be possible, it may be more effective to change the architecture in terms of the associated costs and benefits. Concepts such as the flying wing or blended-wing body have been suggested as the next design point in the trajectory of aircraft architectures . Having said this, architectural changes such as moving the engine location are more likely due to a smaller change propagation, therefore a lower risk for manufacturers. The effect on lift-to-drag ratio and structural efficiency would not be as significant in this case. Hence once again with an architectural change the main driver of improvement in performance would be a decrease in SFC of the engines. This will be associated with a change in engine architecture, since the turbofan architecture as we know it would no longer provide an increase in performance.

It is worth noting that the aircraft operates within an air transport system, therefore there are other systemic factors which need to be considered when viewing this problem. In this paper, the focus is primarily on the technological aspect affecting the performance of a given passenger aircraft. For this reason the main driver of aircraft performance that has been used is the passenger carrying efficiency, a measure of the operating efficiency of a given aircraft. Additionally the focus on the aircraft fuel consumption relative to the number of passengers and aircraft range is a proxy for the economic viability of an particular aircraft. Therefore in the results it is assumed that the mass of fuel consumed is the major driver for aircraft improvement. While this is generally a valid assumption it has been shown that when environmental effects such as contrail formation and NO_x emissions are considered as part of the aircraft performance, decreasing fuel burn does not necessarily translate into increasing performance [56]. In bounding the problem, architecture and performance drivers pertaining to environmental impact, aircraft maintainability and reliability, air traffic management, airline operations, environmental regulations, etc. have not been explicitly considered. Additionally aircraft airworthiness for certification is a major consideration for manufacturers, due to the high costs associated with this process. Certification generally takes a long time, which for manufacturers delays the period by which they may begin making returns on their billions of dollars of development costs. This is one of the main reasons for the risk aversion for manufacturers, since with every new aircraft they are essentially "betting the existence of their company" [57].

7 Conclusion

Since aviation was first commercialized for passenger travel, it has rapidly grown to be one of the most technologically advanced and safe modes of transportation. This development has been associated with advances in the passenger air transport system of systems, particularly developments in aircraft architecture and technology, which have driven continuous improvements in system performance. This paper has focussed on determining when the current dominant aircraft architecture may break by examining the conditions under which it will reach its maximum performance.

It has been argued that there is a tight coupling between engine technologies/architecture and aircraft architecture and a major driver of aircraft performance is specific fuel consumption. Hence advances in turbofan engine technologies have been identified and trends have been used to predict the future performance of civil passenger aircraft. This has been carried out for two possible cases, the first involving existing airframes for a "constrained geometry", and the second involving "unconstrained geometry". A hybrid analytical-empirical model has been described to carry out this analysis for four different engine technology scenarios.

The 737 and A320 airframes were selected to be analyzed for the first case of constrained geometry. It was found that there is still potential to increase performance of these aircraft solely by re-engining. It is shown that the expected date for architecture disruption for the 737 is 2016-2025 depending on the scenario. The equivalent years for the A320 are expected to be 2016-2028. These are the expected years under the technology scenarios that the under-wing turbofan engine infringes on the geometric constraints of the airframe. It is not realistic to assume that in 2017 or 2018 there will be a break in architecture since the 737MAX and A320neo are new aircraft and this does not account for development time of a new aircraft. However this lower bound serves to highlight that the current airframes are reaching their limit and at this point either a new aircraft with the dominant architecture is needed or the architecture will break.

In the second case, the dominant architecture was examined in the context of an unconstrained geometry for the same four engine technology scenarios. It is shown that the expected performance increase is 17.1%, 32.4%, 19.6%, and 39.9% for scenarios 1-4 respectively. These maximum performance increases are expected by 2035, 2043, 2039 and 2045 respectively.

Nevertheless the year of architecture break can be compared and it is shown that the 737 and A320 will likely break within the next 9-12 years, whereas the option for a newly designed aircraft would lead to an architecture break within 27 years. The alternative to these two options would be to develop a new architecture, however this is assumed to occur only after the current architecture reaches its performance limits.

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A Inputs

The specific parameters used to define a mission profile are showing in Table 6. These include parameters defined by the aircraft manufacturer based on market analysis or customer requirements, and the requirements imposed by the Federal Aviation Administration (FAA) in the Federal Aviation Regulations Part 25 (FAR 25), governing airworthiness standards for transport category airplanes [49].

Input parameter	Variable	Description	Units	Typical value
Range	r_{cruise}	The design cruise range of the aircraft	km	5000
Range alternate	$r_{alternate}$	The extra range required to fly to an alternate airport	km	1000
Loiter time	t_{loiter}	The time spent in loiter, waiting for permission to land	hr	1
Pax	N_{pax}	The number of passengers		180
Crew	N_{crew}	The number of crew as dictated by FAR 25		6
Pax/Crew mass	w_{pax}	The mass of the passengers/crew & luggage	kg	100
Cruise altitude	h_{cruise}	The altitude flown during cruise segment	m	10000
Cruise Mach number	M_{cruise}	The Mach number flown during cruise		0.82
Loiter Mach number	M_{loiter}	The Mach number flown during loiter		0.3
Takeoff altitude	h_{to}	The design altitude of takeoff	m	1000
Takeoff field length	$TOFL$	The FAR 25 takeoff length requirement including safety features to account for engine failure situations	m	1500
Approach speed	$V_{approach}$	The speed at which an aircraft approaches a runway for landing. FAR category C for airliners.	ms^{-1}	75
Minimum climb gradient	$\theta_{climb_{min}}$	The minimum rate of climb for a given takeoff scenario, that is $100 \cdot \frac{vertical}{horizontal}$	%	1.2
Obstacle clearance limit	S_a	Clearance requirements for airliner after takeoff. Dictated by FAR 25.	m	330

Table 6: Mission profile variables used as input parameters to the model.

A.1 Technology and design parameter inputs

As well as inputs for the specific mission, the model requires input parameters for technologies within the scope of the analysis. These can be segmented into engine technology inputs and airframe technology inputs, highlighted in the following sections.

A.1.1 Engine inputs

The engine technology inputs are highlighted in Table 7. These pertain to the efficiencies of the major turbofan components, the performance of particular components such as pressure ratios, as well as design parameters such as bypass ratio.

Input parameter	Variable	Description	Units	Typical value
Compressor pressure ratio	P_{r_c}	The ratio of pressure at the front fact of the compressor to that of the back face		30
Fan pressure ratio	P_{r_f}	The ratio of the pressure at the front face of the fan to that of the back face		1.4
Turbine inlet temperature	T_{ti}	The temperature of the flow at the turbine front face	K	1700
Overall pressure ratio	P_{r_o}	The combined pressure ratio across the fan and compressor		50
Bypass ratio	BPR	The ratio of mass flow through the bypass region to the mass flow through the core of the engine		9
Diffuser efficiency	η_d	Efficency of the diffuser in compressing flow		0.97
Fan efficiency	η_f	Efficency of the fan in compressing flow		0.9
Compressor efficiency	η_c	Efficency of the compressor in compressing flow		0.9
Fan nozzle efficiency	η_{fn}	Efficency of the fan nozzle in accelerating flow		0.97
Burner efficiency	η_b	Efficency of the combustor in converting chemical energy of the fuel-air mix to kinetic energy of the flow		0.98
Turbine efficiency	η_t	Efficency of the turbine in extracting energy from the flow		0.98
Nozzle efficiency	η_n	Efficency of the core nozzle in accelerating flow		0.98
Combustor pressure ratio	η_n	Pressure ratio across the combustor		~ 1

Table 7: Engine technology input variables for the engine model.

A.1.2 Airframe inputs

The airframe technology inputs and design parameter inputs for the model can be seen in Table 8. The design parameter inputs are initial assumptions usually based on legacy aircraft.

Input parameter	Variable	Description	Units	Typical value
Lift-to-drag ratio	$\left(\frac{L}{D}\right)_{max}$	The maximum ratio of the aircraft lift to the aircraft drag		18
Zero-lift drag coefficient	C_{D_0}	The coefficient for aircraft parasitic drag which is skin-friction drag plus pressure drag		0.015
Airfoil lift coefficient	$C_{l_{max}}$	The maximum coefficient of lift of the airfoil		1.5
Thickness-to-chord ratio	$\left(\frac{t}{c}\right)_{max_i}$	The ratio of the maximum thickness of the airfoil to the chord length for component i, where i = {wing, horizontal tail, vertical tail}		0.14
Aspect ratio	A_{wing}	The ratio of the square of the wingspan divided by the wing area		8
Taper ratio	λ	The ratio of the chord at the tip to the chord at the root		0.3
Quarter chord sweep angle	$\Lambda_{\frac{c}{4}i}$	The angle of sweep at the line one quarter of the chord aft of the leading edge for component i, where i = {wing, horizontal tail, vertical tail}	$^\circ$	30
Wing dihedral angle	δ_{wing}	The vertical angle of the wing with respect to the horizontal for passive stability	$^\circ$	4
Fuselage fineness ratio	fr_{fus}	The ratio of the length of the fuselage to the maximum width		8
Airplane maximum clean lift coefficient	$C_{L_{max}}$	The maximum lift coefficient for the airplane without any high-lift devices deployed		1.5
Airplane maximum high-lift lift coefficient	$C_{L_{max_{HL}}}$	The maximum lift coefficient for the airplane with high-lift devices deployed		2.4
Oswald's efficiency factor	e	Factor to incorporate difference between ideal wing and 3D wing effects		0.8

Table 8: Airframe technology input variables for the airframe model.

B Outputs

The outputs from the model include aircraft geometry and performance, as shown in Table 9. Additionally a visualization of the aircraft geometry is presented to enable the user to view the design, an example is shown in Figure 8.

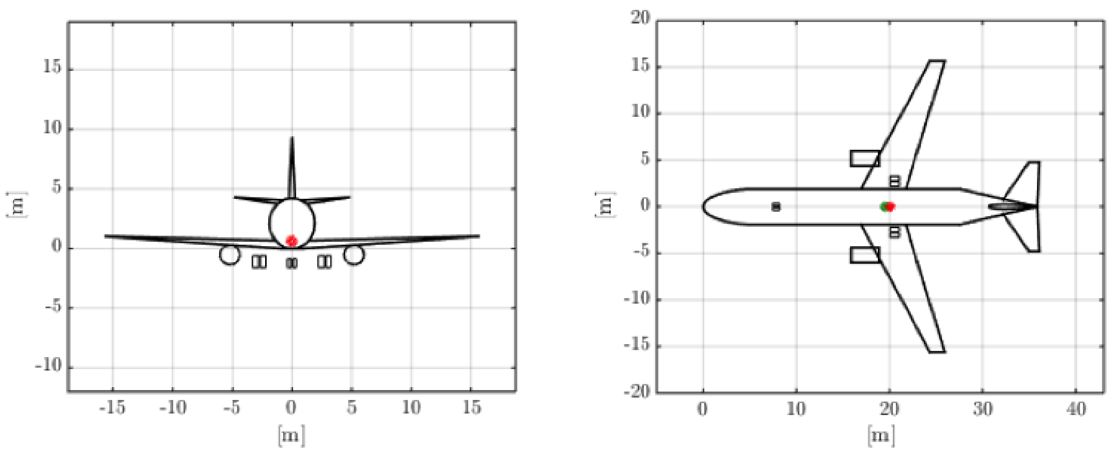


Figure 8: A front-view and plan-view diagram of the output aircraft geometry from the model.

Output parameter	Variable	Description	Units
Maximum takeoff weight	W_{to}	The maximum weight of the aircraft at takeoff	kg
Empty weight	W_e	The weight of the aircraft minus the payload and fuel weight	kg
Fuel weight	W_f	The weight of the aircraft mission fuel including reserves	kg
Component weight	W_c	The weight of aircraft component c, where c = wing, fuselage, HT, VT, engine, main LG, nose LG	kg
Specific fuel consumption	SFC_i	The fuel consumption per unit thrust of the aircraft	$\frac{lbm}{lbf \cdot hr}$
Maximum thrust-to-weight ratio	$(\frac{T}{W})_{max}$	The maximum value of thrust divided by weight across the mission profile	
Breguet range	$r_{Breguet}$	The range of the aircraft as calculated using the Breguet range equation	km
Lift-to-drag ratio	$(\frac{L}{D})_{max}$	The maximum ratio of the aircraft lift to the aircraft drag	
Wing area	S	The planform area of the wing	m^2
Wing span	b	The span of the wing	m
Wing m.a.c.	$\bar{c}$	The mean aerodynamic chord of the wing	m
Fuselage length	l	The length of the fuselage from nose to tip	m
Fuselage diameter	d_{max}	The maximum fuselage diameter, taken as the fuselage height	m
Fuselage width	d_{width}	The lateral width of the fuselage	m
HT area	S_{HT}	The planform area of the horizontal tail	m^2
HT span	b_{HT}	The span of the horizontal tail	m
HT moment arm	l_{HT}	The length from the aerodynamic center of the horizontal tail to the aircraft center of gravity	m
VT area	S_{VT}	The planform area of the vertical tail	m^2
VT span	b_{VT}	The span of the vertical tail	m
VT moment arm	l_{VT}	The length from the aerodynamic center of the vertical tail to the aircraft center of gravity	m
Engine fan diameter	d_{fan}	The diameter of the fan at the turbofan engine inlet	m
Engine diameter	d_{engine}	The diameter of the engine including the nacelle	m
Landing gear track	$l_{LGtrack}$	The distance between the two main landing gear	m
Landing gear wheelbase	l_{LGwb}	The distance between the main landing gear and the nose landing gear	m
Main landing gear tire diameter	d_{main}	The diameter of the main landing gear tire	m
Main landing gear tire width	d_{main}	The width of the main landing gear tire	m

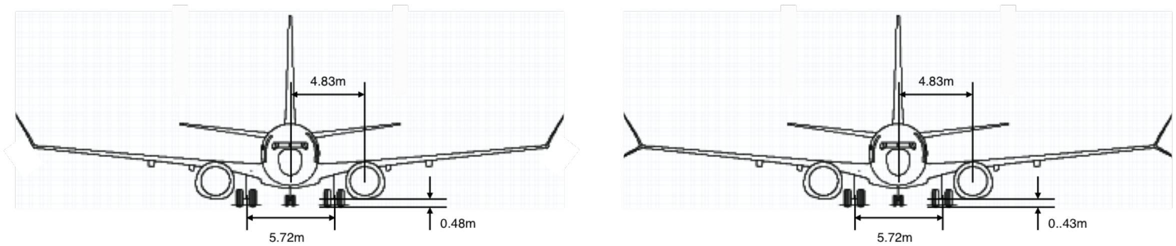
Table 9: Output parameters from the airframe-engine model.

C Airframe and engine geometries and constraints

Parameter	737-800/900 NG [58]	737-7/8/9 MAX [59]	Difference [%]
Engine	CFM56-7B	CFM LEAP-1B	-
Bypass Ratio	5.1	9	76.5
Thrust [lbs]	24,000	23,000 - 28,000	-4.2 - 16.7
Cruise SFC [$\frac{lbm}{lbf \cdot hr}$]	0.60	0.51	-15.0
Fan diameter [m]	1.55	1.76	13.6

Table 10: Comparison of two generations of turbofan engines for the 737.

D Inputs: unconstrained geometry



(a) Boeing 737-800/900 NG

(a) Boeing 737-7/8/9 MAX

Figure 9: Front view drawings of the 737 airframe showing the minimum ground clearance requirement.

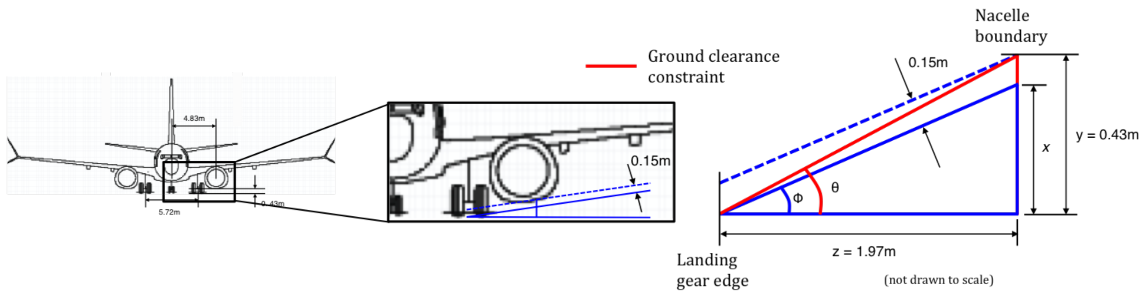
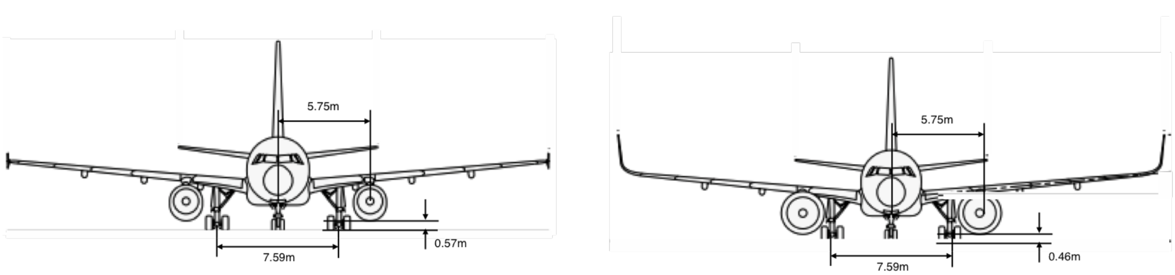


Figure 10: Ground clearance requirement for the engines in the dominant architecture.

Parameter	A320-200 [58]	A320neo [60]	Difference [%]
Engine	CFM56-5B6	CFM LEAP-1A	-
Bypass Ratio	5.9	11	86.4
Thrust $[lbs]$	23,500	24,500-32,900	4.3-40.0
Cruise SFC $[\frac{lbm}{lbf \cdot hr}]$	0.55	0.47	-14.6
Fan diameter $[m]$	1.84	1.98	7.6

Table 11: Comparison of two generations of turbofan engines for the A320.



(a) Airbus A320

(a) Airbus A320neo

Figure 11: Front view drawings of the A320 airframe showing the minimum ground clearance requirement.

Input parameter	Value	Unit
Range r_{cruise}	5000	km
Range alternate $r_{alternate}$	1000	km
Loiter time t_{loiter}	1	hr
Pax N_{pax}	180	
Crew N_{crew}	6	
Pax/Crew mass w_{pax}	100	kg
Cruise altitude h_{cruise}	10000	m
Cruise Mach number M_{cruise}	0.82	
Loiter Mach number M_{loiter}	0.3	
Takeoff altitude h_{to}	0	m
Takeoff field length $TOFL$	1500	m
Approach speed $V_{approach}$	75	ms^{-1}
Minimum climb gradient $\theta_{climb_{min}}$	1.2	%
Obstacle clearance limit S_a	330	m

Table 12: Mission profile variables used as input parameters for the analysis.