# *Architectural options and optimization of suborbital space tourism vehicles*

# Architectural decisions in commercial aircraft from the DC3 to the 787

Demetrios Kellari[1]
*Massachusetts Institute of Technology, Cambridge, MA, 02139*

Edward F. Crawley[2]
*Skolkovo Institute of Science and Technology, Moscow, 143026*
and
Bruce G. Cameron[3]
*Massachusetts Institute of Technology, Cambridge, MA, 02139*

**The volume of passenger air travel has increased rapidly since the first commercially viable passenger aircraft, the DC-3. Over this period, commercial aircraft increasingly appear to have consolidated around a dominant architecture. That is to say, aircraft designers have increasingly made the same architectural decisions (categorical choices such as high wing or low wing), while realizing performance gains in component technologies rather than from major architectural innovations. To quantify the assertion that a dominant architecture has emerged, we analyzed architectural decisions over time, finding a decrease in variation of these decisions in a data set of 157 historical aircraft architectures. We define an architectural performance metric based on passenger-carrying efficiency, technical performance, and market value, observing that in parallel with architectural consolidation, there has been a twofold increase in average performance since the inception of the DC-3. However, the performance trend is shown to follow a trajectory similar to that of a technology S-curve, implying that current improvements in performance with this dominant architecture may be reaching the stage of diminishing returns. Given current levels of activity in engine technology**

[1]Graduate Student Researcher, System Architecture Lab, Room 33-409, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

[2] President, Skolkovo Institute of Science and Technology, Skolkovo Innovation Center, Building 3 Moscow 143026, Russia, AIAA Fellow

[3]Director, System Architecture Lab, Room 33-409, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

**and potential architectural implications of large fan diameters, among other trends, this paper forms the basis for an evaluation of limits to the dominant design.**

## I. Introduction

Over the last eighty years of commercial aviation, the airliner has improved significantly in terms of traditional metrics of aircraft performance, such as fuel efficiency and load factor [1]. These gains have been driven by tremendous technological innovation including in engines, materials, and control systems [2]. This period is associated with a reduction in the variation of architectures and the emergence of a dominant design. In the early years of commercial aviation, there were substantial variations in aircraft architecture. As time has progressed many architectural options, such as engine location above the wing, have died out. This paper examines historical civil aircraft architectures and the trends in these architectural decisions over time.

The conceptual stages of aircraft design comprise high-level decisions pertaining to the aircraft configuration or architecture. An example of such a decision is the vertical location of the wing, taking the options “high wing” or “low wing”. According to Henderson and Clark, 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 [3]. In this context architectural innovation involves a significant change in the linkages between entities of a system without changing the entities themselves. 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. There has been much previous research dedicated to the optimization of design parameters for a single architecture, using multidisciplinary design optimization and other related methods [1], [4]–[6]. Meanwhile there has been significantly less work dedicated to analyzing how major architectures compare in terms of performance.

In the design of large-scale engineering systems, technical decisions made in the early stages have a large bearing on the final system performance [7]–[9]. Said otherwise, revisiting early architectural decisions can force substantial rework due to cascading changes. An example of this issue occurred during the re-design of the U.S. Navy F/A-18 to the Swiss F/A-18 configuration, which increased the cost per aircraft significantly due to unanticipated propagation of changes throughout the system [10].

With the inception of new technologies such as the geared turbofan, we hypothesize that new technologies could force reconsideration of the current dominant commercial aircraft architecture. That is, when incremental improvements of the current architecture are exhausted, technological innovation could drive architectural disruption if there is an associated increase in system performance. For example, if current trends in bypass ratios and hence fan diameter [11] continue, aircraft such as the Boeing 737 may require architectural change to incorporate these innovations.

The objective of this work is to chart the historical evolution of civil aircraft from the perspective of system architecture. This involves identifying and prioritizing the most important architectural decisions and mapping these to past and present passenger aircraft. As a consequence we are able to study which architecture decisions have evolved over time and which have remained stable. By defining a performance metric, based on aircraft efficiency, performance and market value, we are able to track the performance trends alongside the evolution of architectures. Data obtained from aircraft and mission specifications is used to calculate this performance, which is visualized and compared for regional, narrow-body and wide-body aircraft classes. Further, we compute the main effects and interactions of the architectural decisions to analyze the relative impact of each decision.

In Section II we review existing work on aircraft design, aircraft trends over time, architecture representation and enumeration, and various aircraft performance metrics. Section III details the problem formulation, including the definition of architectures in this context and the subset selection of decisions as well as the methods for calculating architecture performance. The analysis of the architecture and performance trends over time is presented in Section IV. Additionally the architecture decisions are prioritized through a sensitivity analysis and the average performance response for each decision-option is examined, before concluding in Section V.

## II. Literature review

We firstly examine work done in the field of aircraft architecture. Following this is an overview of the system architecture field, and more specifically architecture modeled as decisions. The variation of architecture performance over time is analyzed before examining previous research done on the most important decisions in aircraft design.

In aircraft design, the conceptual phase consists of aggregating the design requirements and available technology, culminating in a concept sketch [12], [13]. Usually this also includes an initial sizing whereby domain knowledge from various experts is utilized to roughly approximate the sizes of the various major components. Raymer [12] 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 [14] 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. According to Sadraey [15], in the conceptual phase 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. Howe [16] defines several decisions as being static, namely a cantilever monoplane wing, separate vertical and horizontal tail surfaces, a discrete fuselage and retractable tricycle landing gear. According to Howe the conceptual decisions are therefore the number of engines and their location, the vertical position of the wing and the configuration of the empennage. Meanwhile Torenbeeck [14] details the initial baseline design as comprising of decisions pertaining to wing, fuselage, handling qualities, structural qualities, systems design, powerplant integration. These decisions are motivated by assessment of customer & airworthiness requirements. Although, as previously mentioned, there has been much work done in the realm of optimizing design parameters such as sizes and dimensions [4], [17]–[20], there has been little research done to analyze and quantify the effects of the initial configuration decisions that constitute the aircraft architecture.

Supporting early stage decision-making through system architecting has been a well-studied field in recent years. As such there has been much work done on the definition or enumeration of system architectures. According to Simmons [21], architectures can be defined as decisions, where each decision can be represented by a set of mutually exclusive alternatives. Simmons introduces a process known as the architectural decision graph reasoning cycle, which involves steps in the architecting process including representing, structural reasoning, simulating and viewing. As well as decision-support for system architecture definition there has been research in the domain of decision-support for assessing technologies in the conceptual stages of design. For example, Kirby & Mavris [22], [23] have proposed a method to identify high payoff technology areas to allocate research and development resources efficiently and strategically prioritize and plan portfolios of technologies. They use the Technology Identification, Evaluation, and Selection method [24] to forecast the impact of immature technologies on a system showing that decision makers can effectively mitigate risks associated with uncertainty.

Architectures may be enumerated within a tradespace facilitating the analysis of a group of architectures. This enables one to track their evolution over time, as well as correlate this to the architecture cost and performance. Koo et al. [25] and Arney [26] analyze incremental architectural changes from an initial baseline to identify architectures on the Pareto front in the design space. In the domain of software architecture, Nakamura and Basili [27] trace the evolution of software from the beta until the final version, to analyze the cost of various trajectories and the influence of architecture on this system characteristic. Both Silver et al. [28] and Davison et al. [23, 24] utilized a similar methodology to track architecture development over time taking into account ease of evolution through switching costs. Their motivation was to enhance the flexibility of architecture development pathways and mitigate the uncertainty associated with long lead times.

There has been documentation of historical aircraft design in the form of anecdotal rather than analytical analysis. Gardiner [31] documents the major design trajectories in civil aircraft from the 1930s to the 1980s linking these to the major economic climate of each decade. In his research, rather than considering an overall aircraft architecture, the designs forming these trajectories are characterized by the trends in state of the art of various technologies. These trends include introduction and development of gas turbine engines; the development of new materials such as plastics, fibers and titanium; and, microelectronic control systems. Gardiner notes that "for any design trajectory there are … one-offs that violate the trend", such as the Concorde or flying boats. Miller and Sawers [32] highlight several key advances, which changed the course of the technical development of aircraft from the 1920s to the 1970s, including the introduction of the metallic monoplane architecture with the DC-3 and the use of the jet engine for civil aircraft. Similarly, Green [33] 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 $CO_2$ emission will require radical changes to aircraft design” in particular deviation away from the dominant swept-wing architecture.

In the analysis of multiple architectures, performance metrics are required to track their evolution over time [7]. In the domain of civil aviation, there is an abundance of work tracking the performance of modern aircraft in terms of economic, environmental and operational factors. Aircraft technical performance is typically characterized by payload-range graphs, take-off and landing field lengths, climb performance and cruise performance [12]–[14]. Furthermore there is an abundance of metrics to characterize aircraft productivity. These include aircraft productivity index [34], utilization per day, average stage-length, load factor, available seat mile and revenue passenger mile [35]. Airlines typically use total aircraft block hours, daily airborne hours, number of departures per aircraft day, and other similar metrics to measure their operational efficiency [36]. While these are conventionally used in industry, researchers often devise their own metrics to assess the particular field of interest. For instance, Lee et al. [1] and Babikian et al. [37] 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. [38] have devised a metric known as average temperature response, to quantify the lifetime global mean temperature change caused by aircraft operations. Antoine [5] and Schwartz [39] 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. We chart the performance measures and architectural decisions to identify whether there are trends to suggest another phase of architectural competition driven by underlying technologies.

As well as tracking overall aircraft performance there has been research done into performance trends of individual technologies. Koff [40] highlights the trends in engine technologies such as material properties, combustor design and control systems which have led to a decrease in thrust specific fuel consumption (TSFC) from 0.93 in the mid 1950s to around 0.5 in the late 1990s. A similar study is carried out by Peeters et al. [41], showing that the increase in jet engine efficiency is experiencing diminishing returns; they estimate that the last piston-powered engine was as efficient as the current average jet. In a comparable analysis of engine trends, Birch [42] shows that these trends have limits in terms of performance increase, and potential concepts for future improvement in engine efficiency are suggested. Epstein [11] concludes that the design space for aircraft engines must be extended to experience further performance improvement. Lee [43] believes that it is necessary to expedite technological and operational innovations to improve aircraft powerplant systems.

Finally, the International Air Transport Association (IATA) had devised a Vision 2050, which details the strategic goals for creating a financially sustainable industry while simultaneously halving the emissions compared to 2005 [44]. Extrapolating the trends highlighted by the above researchers, it is clear that the increase in passenger demand will outweigh any decrease in emissions, if current trends increase. While it is unlikely that current trends will continue in this fashion until 2050, given the ambitious goals of IATA, it may not be sufficient to continue with incremental or modular innovations. The future of air passenger travel may rely on considering other areas of the aircraft architectural design space to meet the demands of a future society.

We have reviewed the conceptual stages of aircraft design with a focus on architectural decisions, finding that despite much work being done in optimization of design parameters, there is a dearth of literature in aircraft architectural analysis. We have examined literature on the trends in aircraft architecture, which shows that evolution of aircraft architecture has traditionally been documented anecdotally rather than analytically. In contrast there has been much research done on aircraft performance trends, utilizing various metrics, which highlight a declining rate of improvement over the past eighty years. The goal of this paper is to link the performance and architectural trends analytically and fill this gap in the literature.

## III. Problem formulation

### A. Scope

In order to reasonably compare architectures, consistency in aircraft mission is required. As such this paper focuses on airliners, and excludes military aircraft, sole-purpose cargo aircraft, and rotorcraft. To focus on aircraft serving a consistent set of needs, aircraft with a capacity of less than 30 passengers have been excluded, since design drivers for such aircraft (usually business aircraft or light aircraft) differ from commercial passenger aircraft. A further constraint that is imposed on the set of aircraft is that the minimum number manufactured is 10. This is done to exclude experimental aircraft, which may exhibit aircraft architectures that are not commercially viable, which is a proxy for commercially feasible production and 'value' in the market. It is widely believed that the age of air passenger travel began with the inception of the DC-3 [32]; hence the scope of this analysis will begin from the 1930s, the decade when this aircraft was first produced. Note that dual functionality aircraft such as civil & cargo aircraft are included within the scope of this analysis. The framework developed in this paper can be expanded to include more decision-options, to accommodate architectures that have not been historically produced. For example it has been shown that the blended-wing body aircraft could offer significant performance advantages over current architectures, according to Liebeck [12,13].

## A. Aircraft architecture definition

During the concept creation process, the aircraft architect makes many decisions related to the architecture of the aircraft. A concept, within a given context, is the allocation of function to form. In the case of commercial aircraft the choice between single-aisle or twin-aisle aircraft is often viewed as an architectural decision. The framing of architecture decisions, as defined by Crawley et. al [7], encompasses elements of form which enable these functions to be carried out. The choice between twin-aisle or single-aisle, is a design parameter related to the performance of the aircraft, rather than an architectural decision that enables a new function to be fulfilled. In this paper, the set of architectural decisions are those that enable the most important functions to be fulfilled, such as lifting payload, storing payload, propelling payload, taxiing payload and maintaining stability, control, and trim.

The process of defining aircraft architectures began from the first principles of theoretical system architecture. That is, a functional decomposition was carried out to determine the top-level decisions. For each decision a set of options was created representing the allocation of form to function. That is, an architecture, $i \in I$, consists of set of decision options defined by,

$$i = \{\{d_{ab}\}\} = \{\{d_{1b}\}, \{d_{2b}\}, \dots, \{d_{Nb}\}\} =$$
$$\left\{\{d_{11}, d_{12}, \dots, d_{1m_1}\}, \{d_{21}, d_{22}, \dots, d_{2m_2}\}, \dots, \{d_{N1}, d_{N2}, \dots, d_{Nm_2}\}\right\} \quad (1)$$

where $a = 1,2, \dots N$ represents the architecture decisions and $b = 1,2, \dots, m_a$ represents the respective options that each of these decisions can take. An individual architecture is enumerated by down-selecting a single option, $b$, for each decision, $a$, from each of the decision sets $\{d_{ab}\}$; therefore $\{d_{ab}\}$ gives the set of discrete option values that a given architecture takes. This is distinct from setting the values of design variables such as wing planform area and wingspan, but rather encompasses the decisions with respect to the aircraft configuration at the top level of design. An example of such a decision is the vertical location of the wing, with three distinct options – low wing, mid wing and high wing. In this instance,

$$\{d_{1b} = "wing\ vertical\ location"\} = \{d_{11} = \text{low wing}, d_{12} = \text{mid wing}, d_{13} = "high\ wing"\}.$$

whereby only one of the values in the set can be assigned to this decision. Before explicitly enumerating the architectures, we need to define the measure of performance, which will enable us to refine the architecture model.

## B. Aircraft performance metric

Aircraft performance can be split into multiple components, which include technical performance, operational performance and economic performance. Traditionally performance is measured using metrics such as range, take-off weight, cruise speed, fuel efficiency, lift-to-drag ratio, climb performance, direct operating costs, revenue passenger mile, aircraft price, time out-of-service etc. [13], [47], [48]. To capture the major performance measures at the overall aircraft level, an aggregated metric was devised based on previous work and the availability of historical data. The performance metric, $M_i$, for a given architecture, $i$, can be decomposed into contributions from passenger carrying efficiency (PCE), aircraft technical performance (lift-to-drag ratio, $L/D$, and maximum cruise velocity, V) and market value (list price, P).

$$M_i = w_1 \cdot \left(\frac{PCE_i - PCE_{min}}{PCE_{max} - PCE_{min}}\right) + w_2 \cdot \left(\frac{(T/W)_i - (T/W)_{min}}{(T/W)_{max} - (T/W)_{min}}\right) + w_3 \cdot \left(\frac{V_i - V_{min}}{V_{max} - V_{min}}\right) + w_4 \cdot \left(\frac{P_i - P_{min}}{P_{max} - P_{min}}\right) \tag{2}$$

This is a linear weighted sum of four performance characteristics. The first, passenger carrying efficiency is defined as,

$$PCE_i = \frac{C_i R_i}{(MTOW_i - OWE_i) - A_i C_i} \tag{3}$$

where, $C_i$ denotes the passenger capacity of aircraft $i$, $R_i$ denotes the range with maximum payload, $MTOW_i$ the maximum take-off weight, $OWE_i$ the mass of the aircraft excluding any fuel or payload (operating weight empty[4]) and $A_i$ is the weight assigned to a passenger (75kg person + 25kg baggage). This component can be thought of as the available seat kilometer per kilogram of fuel carried, which is an energy efficiency metric similar to the energy intensity metric devised in [1] or the miles-per-gallon metric for automobiles. That is this measures the ability of an aircraft to carry a specific number of passengers a given distance with respect to the mass of fuel required to do so. McMasters and Cummings [34] cite a similar metric called the aircraft productivity index, used by aircraft designers. Despite its similarity, this was not utilized here to disaggregate the contributions of technical performance and operational performance of aircraft. The second component, the lift-to-drag ratio at cruise conditions is equivalent to the inverse of the thrust-to-weight ratio, that is

$$\left(\frac{1}{(L/D)}\right)_i = \left({}^{T}/_{W}\right)_i = \frac{T_i \cdot N_E}{MTOW_i} \qquad (4)$$

where $T_i$ denotes the thrust per engine at cruise and $N_E$ denotes the number of engines. The lift-to-drag ratio is often used as a proxy for aerodynamic efficiency, which is a common measure of aircraft performance [49]. Since the thrust-to-weight ratio at cruise can be determined from the database this estimate for the lift-to-drag ratio or aerodynamic efficiency can be computed.

As mentioned above, the third and fourth components of this metric correspond to maximum cruise velocity and list price respectively. The maximum cruise velocity is another measure for aircraft performance and is architecturally distinguishing, whereas the list price penalizes more

[4] Note that OWE includes all crew, all fluids, all equipment, but excludes payload (passengers in this case) and fuel weights.

expensive architectures since in reality budget constraints are present. Cruise velocity is used since the comparisons of aircraft architecture are made over the last 80 years where there has been a large variation in this performance metric. Cruise velocity is also used as a proxy for market demand since passengers are willing to pay more for greater speed of travel.

Each of these contributing factors are normalized and form a linear weighted sum, with the weights given by $w_1 = 0.3, w_2 = 0.3, w_3 = 0.3$ and $w_4 = 0.1$. The weights were determined by examining their sensitivity of these to the resulting overall performance. These were adjusted to produce a smooth average performance trend representing continuity in performance over time. Additionally this reaffirms the main objective which is to prioritize the aircraft technical and operational performance.

As noted by Gardiner [31], a metric based on two or three dimensions trying to characterize the performance of such a complex engineering system, naturally only depicts part of the picture. Depicting each and every tradeoff that goes into the design of an aircraft would be nearly impossible, therefore the metric used in this paper is a realistic alternative for high-level performance capture.

## C. Architecture decision subset selection

In this context the aircraft architecture design space consists of the set of conceptual design decisions, which are most impactful on the performance metrics and most connected to other downstream decisions. Given this, it was necessary to analyze the initial set of decision-options, to evaluate which of them are the most important.

The initial design space consisted of 28 decisions, each with multiple options yielding a design space consisting of over $2.5 \times 10^{14}$ potential architectures. The decisions were aggregated from a variety of sources, many of which have been highlighted in the literature review section. Several methods for conceptual aircraft design are described in [12]–[16], as detailed in the literature review. While these sources do not explicitly express architectures as discrete decisions in a well-formulated architecting problem, they do detail the major considerations faced by an architect when attempting to satisfy stakeholder requirements through the design process. In Table 1, the set of high level functions and architectural decision-options associated with these can be viewed. The downselection to the subset of decisions that are most impactful on performance metrics consisted of reviewing existing literature and data analysis. Furthermore analysis of the frequency of options for each decision is carried out, and decisions with only one option over the whole data set are excluded as they don't display any variability. Therefore, by analyzing the frequency of occurrence of each option over time and the sensitivity on the performance metric, the decisions were winnowed.

To carry this out, an architecture was described for each of the 157 aircraft in the database. It is worth noting that the options for each decision encompass a larger space than is present in historic aircraft, therefore the first step was to analyze which options have not been realized in commercial aircraft within the scope of this study. All the decisions in this sample of architectures were examined to observe the frequency of occurrence of each option over time. The goal of this was to determine which decisions only take the value of one option throughout the sample, thus implying that a dominant design exists and this decision should not be considered in our analysis. Having a decision with a single option cannot be defined as an architectural decision in the formulation described above, for the purposes of a historical analysis. Several of these decisions are shown in Fig. 1 for the lifting payload function. It can be seen that the structural configuration decision takes only one option, standalone cantilever as opposed to wire or strut-braced structural integration. Likewise the wing configuration takes a single value of monoplane for the whole sample. These two single-option-value decisions contrast with the wing shape and wing vertical location decisions, which take different values through the sample.

Therefore the former two decisions are removed from the set since they are not architecturally distinguishing. This analysis was repeated for all the decision-options, the entire set as well as the architectural decision subset can be seen in Table 1.

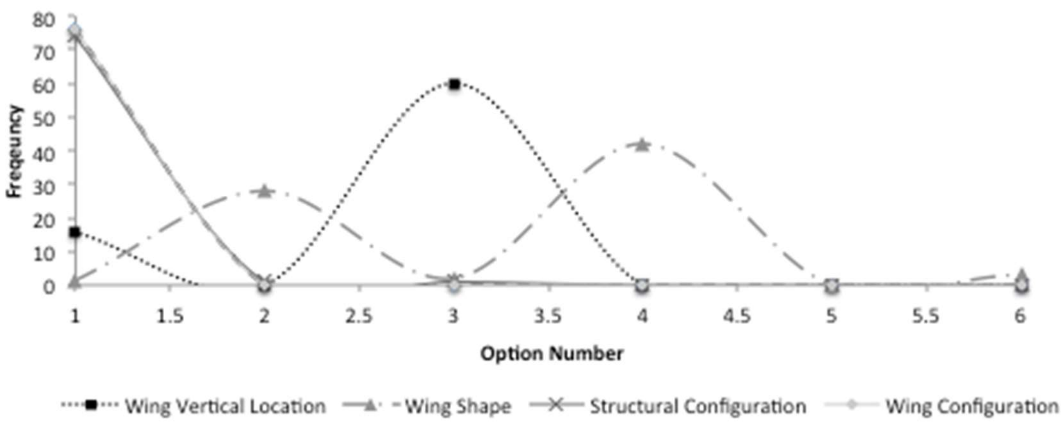



Fig. 1: Frequency of different options for the decisions of how to lift the payload.

The second method employed to refine the decision subset selection was the impact of the decisions on the performance metric. One might imagine that this could be evaluated solely by computing the sensitivity of the performance metric to each of the decisions. Since decisions are often coupled, the sensitivity analysis may be misleading. That is, one could envision a case whereby a non-influential decision takes a different value for a single poor performing architecture leading to a large computed sensitivity. The correlation between poor performance and this decision in such a case would not be causal.

A better approach requires examination of existing literature and domain knowledge to establish a causal link between the performance metric and a given decision. Decisions such as the longitudinal location of horizontal control surfaces, the wing structural configuration and the number of wheels per landing gear are therefore excluded from the architecture definition. While the wing structural integration may dictate local subsystem performance, the overall effect on architectural performance is minimal and usually dictated by a higher priority decision such as engine type. The architecture definition must be detailed enough such that they are distinguishable in the design space; however the decisions need to encompass the allocation of form to function that enables differentiation in the metric space.

A subset of the original decisions emerged as a result, which are highlighted in Table 1 making the design space consist of over 20 million potential architectures, the vast majority of which have never been produced. Note that because of the formulation of the problem in the context of historical architectures all past concepts are not included, including concepts such as blended-wing-body aircraft [45], the MIT D-8, double-bubble concept [50] or a fully morphing aircraft concept [51].

Table 1: Decision options corresponding to the functional decomposition at the third level.

| | Function 1: Lifting payload | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Option 1** | **Option 2** | **Option 3** | **Option 4** | **Option 5** | **Option 6** | **Option 7** |
| **Configuration** | *Monoplane* | Biplane | Triplane | Box Wing | C-wing | Annular Wing | Tandem |
| **Wing Vertical Location*** | *High Wing* | *Mid Wing* | *Low Wing* | *Parasol Wing* | *Shoulder Wing* | | |
| **Wing Shape*** | *Rectangular* | *Tapered* | Delta | *Swept Back* | *Swept Forward* | *Elliptical* | Variable Sweep |
| **Structure** | *Cantilever* | *Strut-braced* | *Wire-Braced* | | | | |
| **Passive Control Shape*** | *Dihedral* | *Anhedral* | *Straight* | Gull-wing | Polyhedral | | |
| **LE devices** | *LE Flap* | *Slat* | *Kruger Flap* | *Leading Edge Slot* | | | |
| **TE devices** | *None* | *Plain Flap* | *Split Flap* | *Slotted Flap* | *Kruger Flap* | *Double slotted flap* | *Triple Slotted Flap* |
| **Tip devices** | *Winglets* | *Wing Fence* | *Downlets* | | | | |

| | Function 2: Storing payload | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Option 1** | **Option 2** | **Option 3** | **Option 4** | **Option 5** | **Option 6** | **Option 7** |
| **Number of Fuselages** | BWB | *1* | 2 | 3 | Flying wing | | |
| **Structure** | Monocoque | *Semi-monocoque* | Truss | Geodisc | | | |
| **Shape** | *Cylindrical* | Airfoil-shaped | *Box-shaped* | | | | |
| **Wing Integration** | *Wing Box carrythrough* | *Blended* | *Ring Frames* | Bending Beam | | | |

| | Function 3: Accelerating payload | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Option 1** | **Option 2** | **Option 3** | **Option 4** | **Option 5** | **Option 6** | **Option 7** |
| **Engine Type*** | *Piston Prop* | Electric | *Turboprop* | *Turbofan* | *Turbojet* | Ramjet | |
| **Number of Engines*** | *1* | *2* | *3* | *4* | 5 | 6 | |
| **Engine Location*** | *Inside Vertical Tail* | *Side of fuselage aft of wing* | Above/in fuselage | Behind fuselage | *Under Wing* | *Above Wing* | *In Wing etc.* |

| | Function 4a: Maintaining stability, control, and trim (pitch) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Option 1** | **Option 2** | **Option 3** | **Option 4** | **Option 5** | **Option 6** | **Option 7** |
| **Configuration** | *Horizontal* | V-shape | Tailless | | | | |
| **Horizontal location** | *Aft of wing* | Canard | Three surface | | | | |
| **Vertical location*** | *Fuselage (Inverted-T)* | Vertical Tail (cruciform) | *Vertical Tail (T-Tail)* | | | | |
| **Shape*** | *Swept back* | *Tapered* | *Straight* | *Elliptical* | | | |
| **Angle** | *Anhedral* | *Dihedral* | *Straight* | Polyhedral | | | |

| | Function 4b: Maintaining stability, control, and trim (yaw) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Option 1** | **Option 2** | **Option 3** | **Option 4** | **Option 5** | **Option 6** | **Option 7** |
| **Configuration** | *1 Standalone surface* | *2 Standalone surfaces* | *3 Standalone surfaces* | V-shaped | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Attachment Location** | *Fuselage* | *On horizontal tail* | *Triple-tail* | | | | |

| | **Function 5: Taxiing payload** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Option 1** | **Option 2** | **Option 3** | **Option 4** | **Option 5** | **Option 6** | **Option 7** |
| **Mechanism** | *Fixed* | *Retractable Enclosed* | *Retractable not enclosed* | | | | |
| **Landing gear type** | *Wheels* | Wheels/Skid | Wheels/Floats | | | | |
| **Landing gear Arrangement*** | *Single Main* | *Tail Dragger* | Bicycle | *Tricycle* | Quadricycle | *Tricycle w/ triple body gear* | |
| **No. wheels nose gear** | *1 wheel bogie* | *2 wheel bogie* | | | | | |
| **No. wheels per body gear** | *1* | *2* | *3* | *4* | *5* | *6* | |
| **Location of stowed landing gear*** | *In the Wing* | *Wing Podded* | *In the Fuselage* | *Fuselage Podded* | *Wing-Fuselage* | *In Nacelle* | |

*decision included in final database set;
*italics*: option appears in historical database;
non-italics: option does not appear in historical database.

# IV. Analysis

Data was collected from a multitude of sources including Jane's and other resource books, Aviation Week and Flight Global archives as well as manufacturer and airline datasheets and archives. The database of airliners used in this analysis includes 157 distinct aircraft and 45 distinct architectures. Preliminary analysis of this dataset yields some interesting trends over time, which can be seen in the figures below.

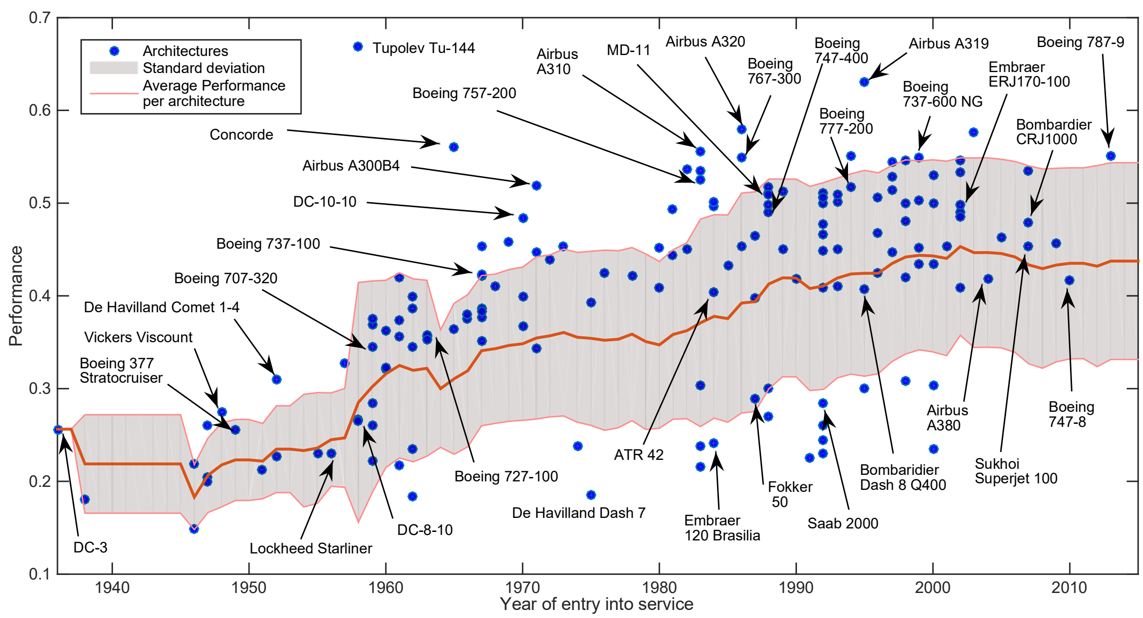



Fig. 2: Performance of aircraft architectures including the year-averaged performance and standard deviation over time.

From Fig. 2 it can be observed that over the past 80 years the performance has more than doubled. Compared to domains such as electronics, where there is exponential growth according to Moore's Law [52], this may seem like a small improvement; however this is a significant improvement when one considers that automobiles have experienced approximately the same twofold improvement over the past 120 years [53]. Moreover aircraft safety has improved significantly, decreasing from over 50 incidents per million departures in the 1960s to less than 2 today [54]. Safety has not been incorporated as part of the performance metric mainly due to a dearth of available data from the early years of commercial aviation.

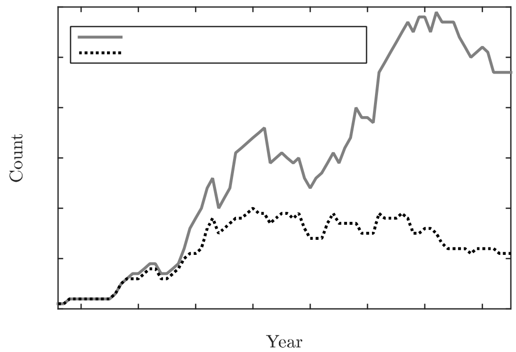
The highest performing architecture according to the defined metric is that of the Tupolev Tu-144, a supersonic jet, which was in fact grounded after a mere 55 passenger flights and 102 commercial flights due to economic and safety reasons [55]. This highlights one of the limitations of examining the architecture performance using this view. Meanwhile, the Airbus A319 can be seen to be the highest performing of the rest of the architectures. Including cost factors as well as safety factors in the analysis is not within the scope of this paper, however it is a topic for further research.

### A. Architecture variation over time

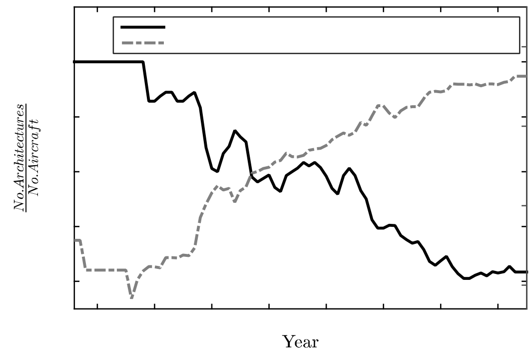
The history of passenger aircraft development is filled with considerable nuances, involving geopolitics, government subsidies, various stakeholder interests and many other effects, which could not be captured in this analysis.

It is commonly known that before the 1930s aircraft varied significantly in their architecture and technology, however tracking these is beyond the scope of this paper. Given the extensive data collected to create the database of architectures, it has been possible to track the number of distinct architectures over time. Fig. 3a shows the trend in the number of distinct aircraft being produced and the number of distinct architectures among these aircraft. In Fig. 3b, the ratio of these two at a given time in history and the yearly average performance for the architectures, are shown. This ratio gives us the variation in architecture at a given point in time by telling us what proportion of the aircraft manufactured at a given point in time have different architectures.

a)




a) Distinct architectures and distinct aircraft per year




b) Ratio of distinct architectures to distinct aircraft and architecture performance

Fig. 3: Analysis of architectures over time

It is evident from the figure that the number of distinct aircraft being produced has increased from approximately 3 to over 50 in the 80 year timeframe, for those aircraft that fall within the scope of the analysis. Intriguingly it can be seen that the number of distinct architectures increased in parallel with this from 1936 to the late 1950s at which point these two graphs diverge. The number of architectures remains fairly constant for the next 40 years until approximately 2000 where it can be seen that the variation in architectures is in fact decreasing.

The solid line in Fig. 3b clearly displays the decrease in variation of architectures over this period of time. This graph can be further analyzed using Fig. 4.

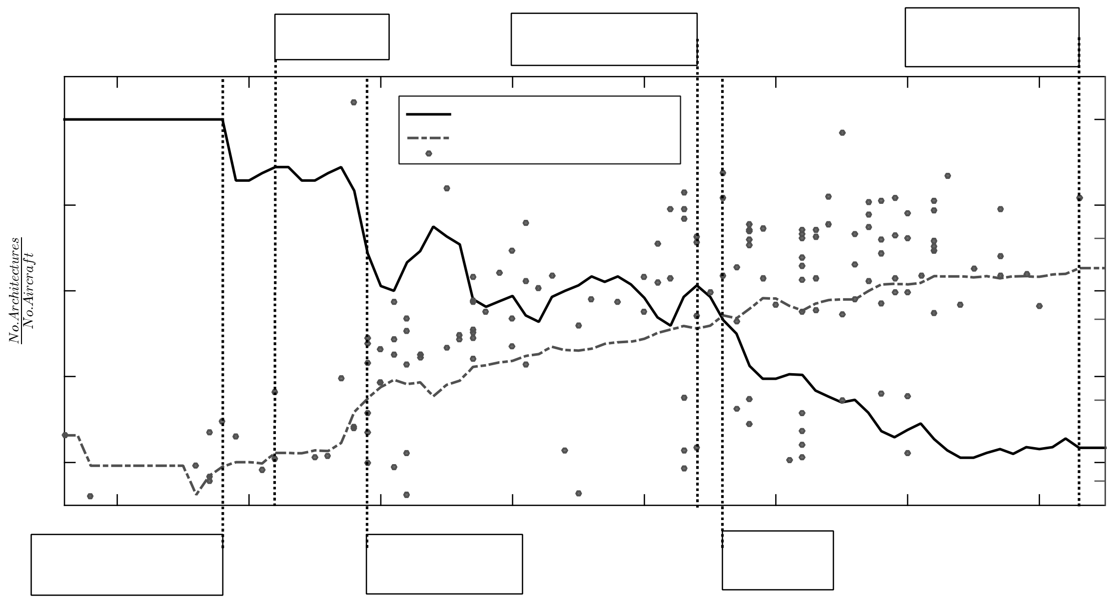



Fig. 4: Ratio of distinct architectures to distinct aircraft over time overlaid with yearly averaged performance over time.

The graph showing the variation in number of architectures over time shows that until the early 1960s architectural innovation is occurring. This is evident due to continuous increase in the number of distinct architectures during this period. Additionally, this timeframe is associated with a number of new technology introductions, particularly in engine technology, as can be seen in Fig. 4.

In the post-1960 era, the number of architectures remains relatively constant until the early 1990s. The ratio of number of architectures to number of aircraft decreases in this period, demonstrating that more aircraft of the same architecture were being produced. This suggests the end of the architecture exploration stage and a period of incremental innovation. This point is reinforced by the steady increase in performance during this period, which is indicative of incremental product innovations.

From 1990 to the present day there are indications of architectural consolidation in civil airliners. The number of distinct architectures during this period is steadily decreasing, indicating the emergence of a dominant design. It is notable that the largest decrease in the ratio of architectures to aircraft occurs immediately after the EPA released environmental standards for hydrocarbon and other emissions in civil aviation. One might hypothesize that architectures which could not possibly comply with such standards begun to be phased out at this point in time. Along with architecture performance, such external driving forces may have caused this emergence of a dominant design.

A major driving force in the emergence of dominant designs in aircraft architecture is the inheritance of type certification for aircrafts and the development of aircraft families. According to Howe [16], in many successful aircraft, the design is a direct development of an earlier type. The reasons being that to be commercially viable a new aircraft must be a technical improvement upon its predecessors and risks are mitigated through utilizing existing knowledge and legacy designs. Howe states that therefore a lack of experience, uncertainty of design data, and customer reservations usually eliminate unconventional configurations. This phenomenon will not be analyzed in depth in this paper, however it is one of the many factors that has shaped these architectural trends.

## B. Architecture performance

To control for the effects of scale, it is possible to stratify the data set according to mission type. That is regional, narrow body and wide body aircraft can be separated to enable us to dive deeper into these trends. For each aircraft architecture the performance metric described in Section 3 was evaluated to measure the ability to efficiently transport passengers a given distance as fast as possible, given the price and technical characteristics of the aircraft. Through stratification of the aforementioned different aircraft classes, we further ensure that architectures are comparable based on the more homogenous mission profiles.

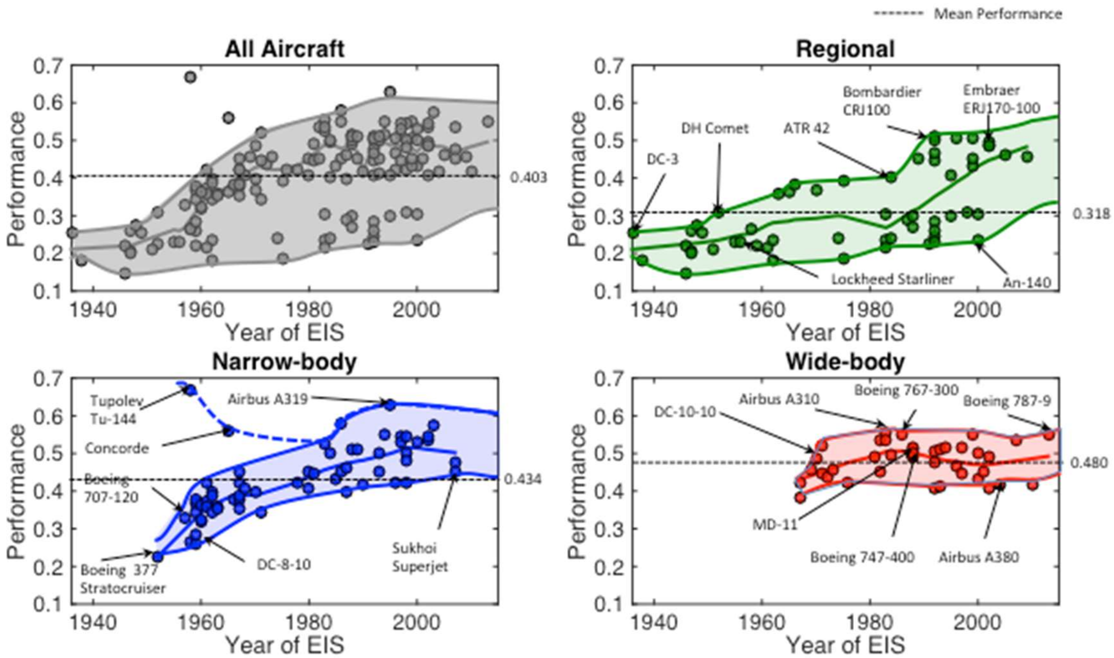



Fig. 5: Yearly averaged performance for stratified data sets by aircraft type, showing mean performance and range.

Included on the four graphs of Fig. 5 are boundaries around the range of performance at a given time, with the exception of the two supersonic passenger jets, and a trend line of the average performance per year. As previously mentioned, an amalgamation of the many tradeoffs that go into the design of an aircraft into a single performance metric cannot possibly capture the whole picture. Each individual architecture has been optimized for its specific mission purposes and thus the variance is accounted for by this phenomenon. The motivation for stratification can be observed in this figure where the differences in the mean performance of each set is evident. As expected the effects of scale can be seen, that is, the larger aircraft types are generally higher performing due to the efficiencies captured at this scale.

The overall performance trend can be seen to follow a curve similar to that of a technology S-curve [56]–[59], starting with a period of constant performance, followed by a period of performance increases with a decline in the rate of these improvements. Examining the trends of the different aircraft types in terms of the overall group rather than the yearly average, it is noticeable that they too follow a similar trajectory. As mentioned previously, the majority of architectural exploration occurred in non-commercial passenger aircraft prior to the 1930s, therefore one would expect a period of constant performance during the very early years of aviation, which would emphasize this S-curve shape. In the period from the early 1990s until the present day the progress of the previous years slowed down as architecture performance matured and approached a ceiling. This phenomenon is an innate characteristic of the aforementioned architectural consolidation, since incremental or modular innovations eventually lead to diminishing returns in performance [58].

From Fig. 5 it can immediately be seen that the dates of entry into service between different aircraft types are staggered, that is, as time progressed larger aircraft became more widely available. There are common architectures across these stratified groups and variations in architecture within them, which is shown in Appendix A. Therefore this trend in size can be attributed to technological advances, such as in structures and materials with the inception topological optimization and composites. Comparing these graphs with that of Fig. 4 one can make observations about these technological innovations in the context of the various aircraft types. The start of narrow-body aircraft coincides with the introduction of turboprop aircraft and likewise the beginning of wide-body aircraft coincides with the introduction of turbofan aircraft. On an aircraft systems level, the advantages of each of these technologies is well-known [40]; however there has been little research done from the perspective of architectures in a tradespace. This work shows the influence of engine technology on aircraft architecture. With new engine technologies on the horizon, such as the geared turbofan, it is possible that we will see a new age of aircraft architectural exploration driven by engine innovation.

An interesting observation for wide-body aircraft is the increase in performance for these has been very marginal over the past forty to fifty years. This is in stark contrast to the regional and narrow body types, which have experienced more than doubling in performance. Considering that architectures such as that of the Boeing 747 have persisted for over forty years, this observation is hardly surprising; in fact the variation of architectures within this group will be shown to be fairly small, which may contribute to this effect. Additionally it has been well documented that the beneficial performance effects of scaling aircraft diminish beyond a certain size [60], [61]. Hence one could conclude that, given architectural consolidation and the dominance of incremental innovation, these aircraft lie at the limit of diminishing marginal returns on performance.

## C. Architectural decision space

With a large database of architectures, one can utilize data mining techniques to extract significant insights into the implications of architectural decisions on performance. To do so we compute the sensitivity of each decision in the metric space, and the connectivity or degree of coupling of these decisions. Each of these is explained below.

### *Sensitivity*

The sensitivity of a decision in the metric space is a measure of the degree of influence of that decision on that particular metric [7]. In dealing with decisions with more than binary variables, the sensitivity is calculated for a group of architectures $i \in I$, with possible architectural decisions $D_j$ that have option values given by $z \in Z$. $N_{1,z}$ is the number of architectures for which the value of decision $D_j$ is set to option $z$ and $N_{0,z}$ is the number of architectures where $D_j$ is not set to $z$. In this way we are averaging the difference in the performance metric $M(x)$ with the decision taking the value of one option over not taking the value of that option.

$$S(D_j, M) = \frac{1}{Z} \sum_{z \in Z} \left| \frac{1}{N_{1,z}} \sum_{\{i | i_{D_j} = z\}} M(i) - \frac{1}{N_{0,k}} \sum_{\{i | i_{D_j} \neq z\}} M(i) \right| \quad (5)$$

***Connectivity***

Since architectural decisions are often coupled, a measure is required to capture this interdependence, which influences change propagation in the design process. A design structure matrix (DSM) was used with the constraints representing relationships between the various decisions forming the rows and columns of the matrix. It is evident that there is an element of subjectivity in this formulation, firstly because it is dependent on the formulation of the architectural decisions [62] and secondly it is dependent on a priori knowledge in which the definition of a relationship is fuzzy and may be subjective. Despite these shortcomings the DSM is a commonly used tool in system architecture due to the ability to capture and visualize complexity in engineering systems. The connectivity using this method is the number of connections between one decision and the others (this is between 0 and 1 since it is normalized by the maximum number of possible connections), which are captured in aircraft design books such as Roskam [13] and Raymer [12]. The resulting relationships between decisions are shown in Fig. 6 in the form of a graph, rather than a DSM in order to visualize these better, where a directional arrow indicates either a strong or a weak influence of the source decision over the sink decision.

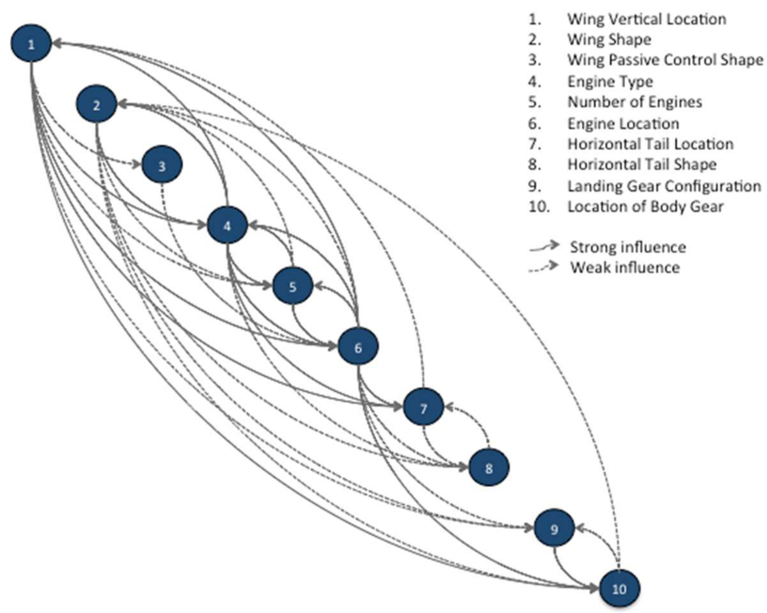



Fig. 6: A graph of the decision space showing interconnections between the decisions.

### ***Decision space view***

Plotting the sensitivity against the connectivity for each of the architectural decisions, architectural decisions can be prioritized.

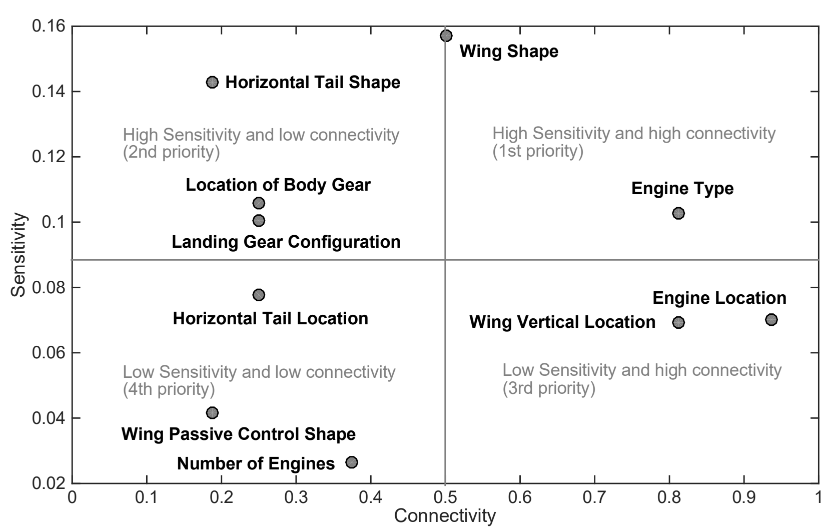



Fig. 7: Sensitivity of the decisions to the performance metric against connectivity of each decision.

The results for the whole dataset of architectures can be seen in Fig. 7. The architectural decisions can be prioritized by categorizing the space into a 2-by-2 matrix of sensitivity against a normalized connectivity, with the highest priority decisions being located in the top right quadrant. It can be observed for this formulation of the aircraft architectures, the decisions pertaining to engine type and wing shape are those that take priority.

It is worth noting that by making a given decision, the design space becomes restricted by any constraints that the value of the decision imposes. For example, by selecting ‘Engine Type’ as a ‘turboprop’, the ‘Wing Vertical Location’ decision is usually going to be ‘high-wing’, due to the physical constraints imposed by having an engine with a large propeller. In other words, these two decisions are closely coupled; therefore by ranking the decisions in order of importance and keeping track of cascading constraints during architecture enumeration, any potential conflicts can be minimized.

The decisions in the upper left quadrant are made second – these are decisions that have a large effect on performance of the architecture depending on the value they take, but are not closely coupled with many other decisions. In this context it is important to note that the correlation between a decision and the aircraft performance does not imply causation. For example, the horizontal tail shape is often closely coupled to the shape of the wing and the engine type, therefore the high sensitivity is as a result of this coupling rather than as a direct effect of the value taken by this decision in isolation.

Interestingly, the location of the landing gear and the landing gear configuration decisions seemingly have a large effect on the aircraft performance. The reason for this is that higher performing architectures are associated with larger aircraft in general, and larger aircraft require different landing gear configuration and landing gear location than smaller aircraft. Once again in this instance the correlation can be explained by the connectivity between the decisions, rather than a direct causation of these decisions. In addition, upstream effects such as the aircraft mission profile which influence the aircraft decisions and scale also have an impact on the architecture performance. It is possible that in further work mission decisions could be formulated as architectural decisions and included in a similar analysis.

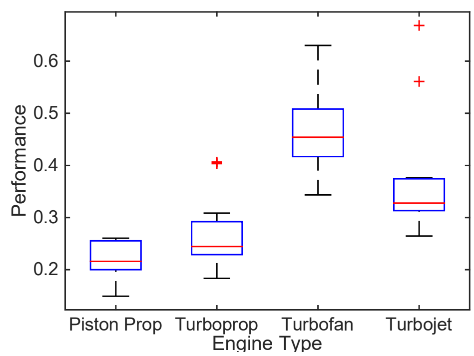
In the bottom left quadrant are located the lowest priority decisions, one of these being the number of engines on the aircraft. This result suggests that selecting the number of engines does not change the performance of the aircraft significantly for 2 engines versus 3 or 4 engines, for example. Considering the performance metric definition, factors such as direct operating costs including maintenance are not captured in this view, which is one of the major benefits in a fewer number of engines.

### D. Relationship between architectural decisions and performance

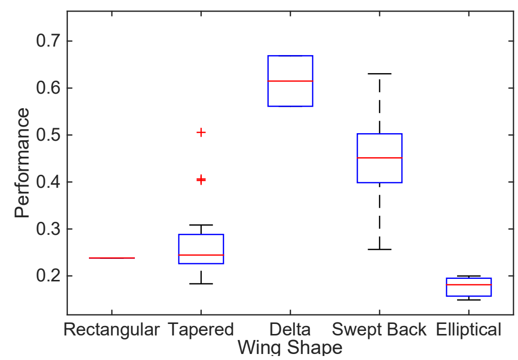
Given this dataset, it is possible to visualize the relationship between architectural decision-options and performance. Plots of four decisions showing the mean, interquartile range, range and perceived outliers are shown in Fig. 8.

Examining the 'Engine Type' decision it can be seen that turbofan engines are associated with architectures of higher performance. One must note here that the correlation does not imply that a high performing architecture is caused by any given decision, since there are interaction effects and coupling which are not displayed in this view of the architectures. Similarly delta wing shapes are the highest performing followed by swept-back wings, due to the fact that this architectural decision is associated with supersonic passenger aircraft.

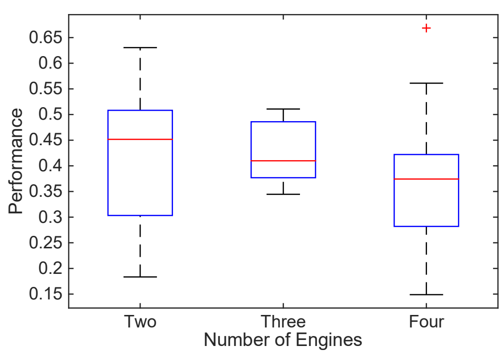
The correlation between number of engines and performance is interesting, since it can be seen that increasing the option from two to four engines corresponds to a decrease in performance on average. The time variation of these decision-options can be seen on the graphs in Appendix A. In the case of the 'Number of Engines', clusters of each option can be seen in the time-performance space. It can be seen that on average, over time, architectures have shifted from a four-engine architecture to a two-engine architecture, in parallel with an increase in architecture performance. An improvement in engine performance and reliability enabled this switch, which improves passenger carrying efficiency and decreases maintenance costs for twin-engine aircraft.



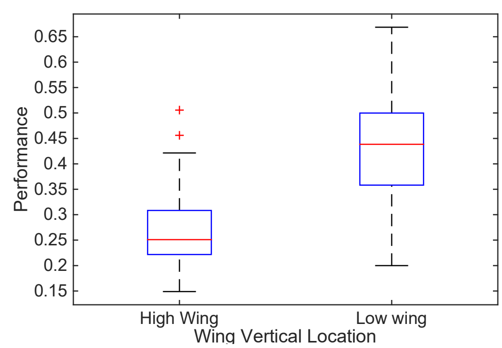

a) Engine Type




b) Wing Shape




c) Number of Engines




d) Wing Vertical Location

Fig. 8: Box plot of performance of each option for four decisions.

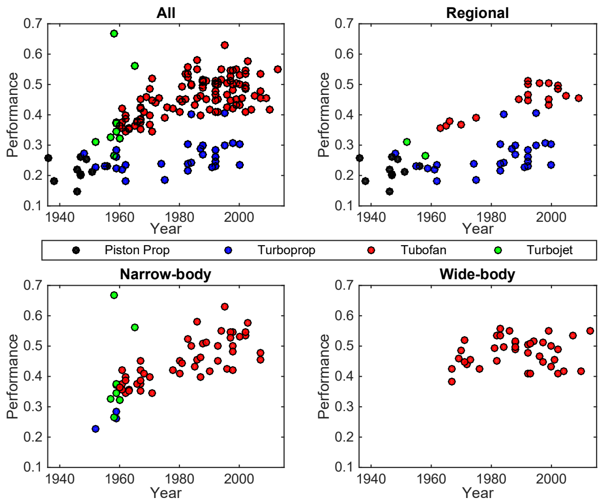
## V. Conclusion

Architectural decisions represent categorical choices made early in the design of an aircraft. This paper enumerates a possible set of these decisions The benefit of this analysis in aircraft conceptual design is in applying a structured approach, which makes explicit the key decisions and their implications on architectural performance. While previously aircraft conceptual design was based on domain knowledge and prior experience of the architect, the results here have provided a quantitative approach using historical architectures to prioritize the major architectural decisions and their relationship to performance.

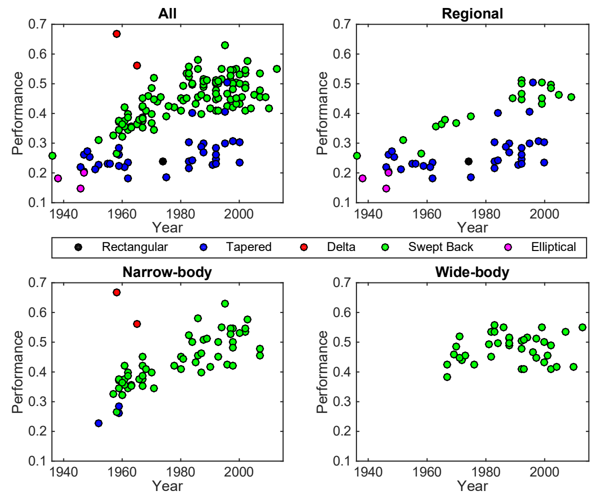
It has been shown that over the past eighty years, the variation in architectural decision-options has decreased and a dominant architectural design has emerged. While this is easily observed from a survey of aircraft, this paper quantifies that variation in concert with the performance gains that have been made - the performance of aircraft on average has increased by over two times. The architecture performance over this period has followed a trajectory similar to that of a technology S-curve. This performance trend is dependent on the selection of metrics and the weights used. The metrics have been selected based on available data and the weights have been computed by carrying out sensitivity studies that result in a smooth average trend over time. If the focus of the analysis were on one particular factor such as aircraft fuel burn it would be necessary to adjust the weights to reflect this. Since architectural performance was the focus of this paper it was assumed that operational, economic and technical factors were important.

These trends imply that passenger aircraft have gone through a period of architectural innovation followed by incremental and modular innovation mainly in propulsion and materials technologies. It has been shown that, historically, innovations in engine technology have led to aircraft architectural innovation. A next step would be to examine the trends in engine technology to attempt to predict the implications on aircraft architecture. History would suggest that there are limits to the performance gains from every architecture, and that fuel price gains, technology maturation, or new regulations could force consideration of alternative architecture to realize performance beyond the incremental growth trend seen today.

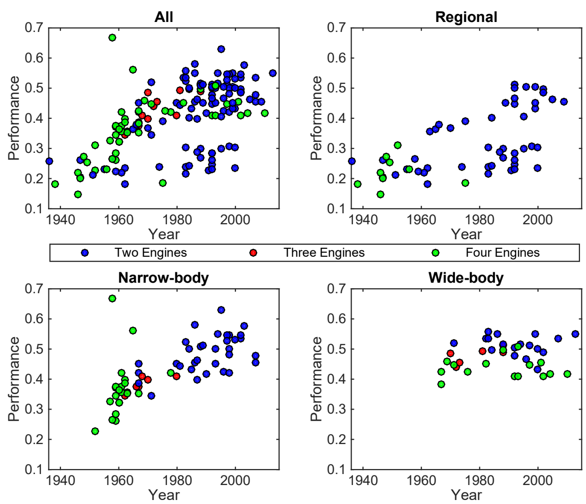
# Appendix A



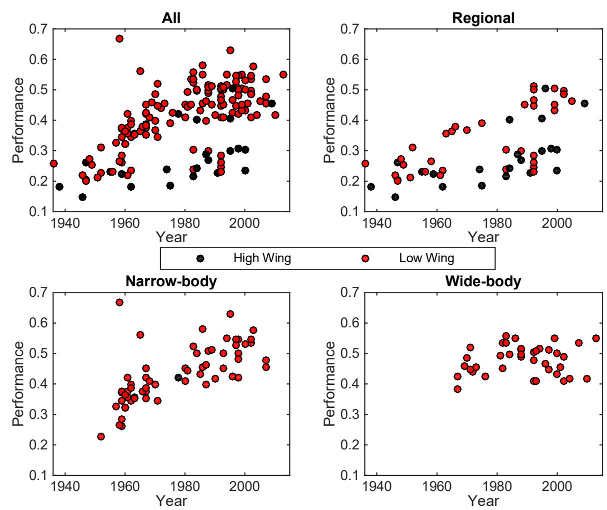

a) Engine type




b) Wing shape




c) Number of engines




d) Wing vertical location

Fig. 9: Trends in architectural decision-options over time plotted in performance-time space.

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