COMBINED AIRFRAME AND SUBSYSTEMS EVOLVABILITY EXPLORATION DURING CONCEPTUAL DESIGN

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Abstract

Evolvable designs allow development costs of future products to be lowered significantly. This work contributes to aircraft conceptual design space exploration by enabling simultaneous combined exploration of both airframe and subsystem evolvability. This is made possible by combining existing subsystems-architecting and design space exploration techniques with novel commonality assessment algorithms. The proposed techniques are demonstrated via a simple single-aisle passenger aircraft evolvability study.

1 Introduction

Evolvability is a vital consideration during the design of a new aircraft. It refers to the extent to which components, subsystems, and associated processes (e.g. manufacturing) of the design can be reused or changed with 'little effort' to be incorporated into possible future products. That is, aircraft manufacturers often attempt to retain as much commonality between previous, current, and future designs, while trying to prevent compromising performance unduly. The following definition for evolvability is adopted here:

> *Evolvability:* The ability of a system design to be inherited and changed across generations (over time) [1].

The purpose of designing for evolvability is to (hopefully) foster shorter development times and lower the development cost of subsequent generations of the design, amongst others.

Several systematic methods for designing for and exploring evolvability during conceptual design have emerged over the past few years, such as in Lim [2]. However, these usually require 'change rules' (or commonality) to be specified a priory and either focus exclusively on the airframe (i.e. the wing, fuselage, empennage, and undercarriage) or the subsystems (such as the hydraulic, pneumatic, and electrical power systems, the environmental control system, and so forth).

In this paper, a framework is proposed that promotes evolvability exploration of the combined airframe-subsystems unit. Particularly, it enables searching for commonality across the airframes and subsystems of pairs of input aircraft designs, rather than requiring this commonality to be 'pre-specified'. An important contribution is that the framework allows input airframes and subsystems pairs that have dissimilar architectures (i.e. having possible different constituent components and/or layouts of these components). This makes it useful for exploring evolvability across conventional and novel configurations.

The paper constitutes an extension of the research presented in the doctoral dissertation of A.S.J van Heerden [3] and is organised as follows: This introduction is followed in Section 2 by a discussion on designing for evolvability in conceptual design. In Section 3, the combined airframe-subsystems evolvability exploration framework is introduced, followed by a demonstration of how it could be used (Section 4). Conclusions are presented in Section 5.

2 Background

In this section, a brief overview of important concepts regarding designing for evolvability is provided. First, the concepts of evolvability and commonality are described in further detail, followed by a discussion on the design activity of evolvability exploration.

2.1 Evolvability and Commonality

Whether it was planned or not, many aircraft designs (both military and civil) have undergone significant evolution. For selected case studies regarding the evolvability of military aircraft, the reader is referred to Lim [2]. Many civil passenger aircraft have also been subject to substantial redesign to meet new requirements and remain competitive. An exemplary case is the Boeing 737 design, which has twice been upgraded with new engines; undergone substantial changes to increase wing area (through chord increases, larger control surfaces, and tip extensions); had 'plugs' inserted to increase fuselage length; and received extensions to the empennage surfaces to increase surface area, amongst many others.

Despite these changes across the generations of 737s, much of the original airframe design has been re-used. This reuse of design features (as well as the associated processes) on later generations of a design implies 'commonality' with the baseline design. According to Boas [4], commonality is the "sharing of components, processes, technologies, interfaces and/or infrastructure across a product family" . It provides many life cycle benefits [5], but the focus here is on its potential to reduce development time and cost (often referred to as Research, Development, Test, and Evaluation (RDT & E) costs, as well as manufacturing cost and time. Development time and cost are reduced, because the total 'development scope' is reduced [4]. Furthermore, development of the first product is generally expected to cost more than if no commonality was planned, whereas subsequent variants are expected to cost less [4]. Manufacturing cost is also expected to be lower for the first unit of a subsequent variant, as some components/parts would be positioned further along the production 'learning curve' if those components/parts are already being manufactured for the baseline [4].

Commonality is therefore related to the reduction of redesign effort for a new descendant. To quantify this benefit, either a commonality score could be employed (which is only valid for comparison when the same baseline is used) or the development and manufacturing cost reduction could be estimated. A commonality metric (also called commonality 'score' or 'index') is a quantitative measure that aids in product evolvability related decision-making [6]. Many such metrics have been proposed and, for an overview, the reader is directed to Pirmoradi et al. [7]. Simple mass and cost weighted metrics are used in this paper (see Section 3).

2.2 Evolvability Exploration

The term 'evolvability exploration' is used here to refer to the activity of searching for aircraft designs that appear promising for the 'near-future' entry-into-service (EIS) timeframe and could be changed with relatively little redesign effort to future designs that provide value in the possible 'far-future' timeframes.

One of the pre-eminent methods for design space exploration (particularly for evolvability exploration) is 'multi-attribute tradespace exploration' (MATE). MATE is an approach in which formal decision theory (particularly multi-attribute utility theory) is incorporated into model- and simulation-based design [8]. The multi-attribute tradespace is a two-dimensional tradespace in which the ordinate represents multi-attribute utility and the abscissa cost. This plot is populated by all the enumerated designs, such that each design is represented by a utility/cost point. This enables the decision-makers to view the value and cost of all the designs under consideration in a single plot, regardless of the different subsystems architectures and configurations the designs may embody.

The temporal nature of the environment in which complex systems operate can be accounted for by combining MATE with a process called 'Epoch-Era Analysis' (EEA) [9]. In EEA, the full life cycle is referred to as the 'era', whereas epochs refer to periods of time within that life cycle in which the context (factors exogenous to the system) remain 'constant' and the system provides fixed value [9]. Each epoch is subsequently characterised by "static constraints, available design concepts, available technology, and articulated attributes" [9]. Each epoch can therefore be represented as a separate MAT. As a new epoch dawns, the changes in requirements, available technologies, regulatory environments, and so forth, could have an effect on the value of the system and its utility may increase or decrease. Several authors have applied a combination of MATE and EEA specifically to the exploration of evolvability in complex systems (see for example Refs [10], [11], and [12].

Most evolvability exploration techniques usually assume that the change rules (change mechanisms) between different designs are already specified. However, it would be beneficial if techniques were available that could automatically determine which components/parts could be common or non-common, and if these are combined with the exploration methods, the designer could focus on ways to increase the commonality, or render non-common items 'easier' to change across designs. Some authors have indeed already proposed to use design/trade space exploration for such a purpose (see for example Refs [13], [12], and [14]). These are interactive methods and are useful and powerful. However, only a limited number of variables could conceivably be managed by the designer. Also, in all of these methods, either only a single system architecture was used, or commonality was only searched for in component pairs that were known to be described by the same set of parameters. The methods will not work as-is for systems with dissimilar architectures/configurations or where the geometry may differ across similar types of components. Finally, none of them are automatic, which could be problematic when the number of designs, configurations, and scenarios are high. To overcome these issues, there is a need for techniques that could *automatically*:

- determine which major airframe components across two different aircraft are of the same type and connected to other components in the same way, such that they could be send for more detailed similarity assessment; and
- identify similar segments (based on user criteria) across pairs of components that have complex geometries, complex mass distributions, several attachments to other components, and so forth.

Such techniques were developed in Ref [3]. However, it would also be beneficial if the techniques could assess commonality across airframes and subsystems in a combined fashion. This is because subsystems are being increasingly studied earlier in the overall aircraft design process (see for example Bile et al. [15]). Extending the techniques from Ref [3] to provide a combined airframe-subsystems is the subject of this paper and the combined approach is provided next.

3 Framework

An overview of the airframe-subsystems evolvability exploration framework is provided in Figure 1. As can be seen, it prescribes a process where scenario, airframe, subsystems, and propulsion modelling is followed by the integration of the created models. These are then sent to a dedicated sizing and performance workflow to create a population of potential designs. These designs can then be explored interactively using tradespace exploration techniques. Promising near- and far-future designs are then selected for commonality prediction. The results of the commonality prediction are subsequently included in the tradespaces and the process continues, until suitable solutions are found.

Automatic commonality prediction is the main focus of this paper and a diagram of the process followed can be viewed in Figure 2. The inputs are specifications of the two aircraft and commonality prediction (CP) parameters. The former are objects of a class 'Aircraft', which

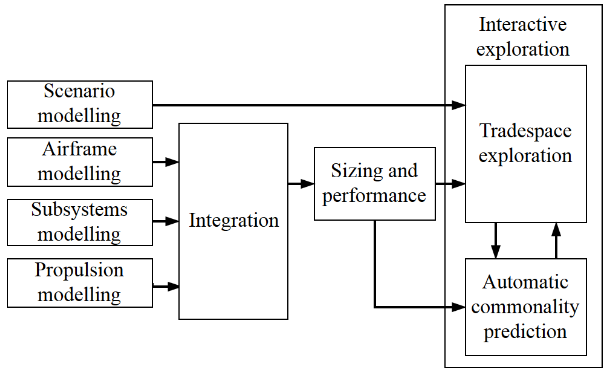


Fig. 1 Airframe-subsystems evolvability exploration framework

contain detailed structured data on the geometry, mass (including mass distributions), and cost of the airframe, engines, and subsystems. From this object model, a Design Structure Matrix (DSM) can be created. The CP parameters include information such as tolerance values and discretization specifications for the geometry.

The aircraft objects are sent to the partitioning module, which determines which component pairs (i.e. from the two aircraft) can be scrutinised for commonality. The components pairs for the airframe, subsystems and engines are then dispatched to the dedicated commonality prediction modules. The output of these are data objects that include commonality matrices (specifying which components or subsegments of components are common with each other) and mass and cost commonality scores. The commonality information for the airframe, subsystems, and propulsion are then combined in commonality aggregation module to provide overall mass and cost commonality scores. Each of these modules are presented in more detail next.

3.1 Partitioning

As stated before, the partitioning module determines which pairs of components should be compared in detail to compute commonality. It does this by parsing the DSMs created for the two aircraft (a and b). The DSM compactly stores important component and topology information for a selected aircraft. Component information could include type (e.g. 'turbofan', 'turboprop', or 'ramjet' for components of class 'engine'), spatial orientation, and symmetry information, amongst others, whereas topology refers to the manner in which the constituent components are connected to each other.

Let the DSM be called $\mathbf{D}$ and let the set of components which constitute the aircraft be denoted as follows:

$$C = \{c_1, c_2, \ldots, c_k, \ldots, c_n\}. \quad (1)$$

The number of components is therefore n. $\mathbf{D}$ is defined here as a square matrix of size $n \times n$, where the entries in row k and those in column k contain information on how the k^{th} component are connected to the other components. The diagonal entries contain information regarding the component in the corresponding row/column itself. This includes orientation, symmetry, and type of the component, amongst others. The off-diagonal entries contain information regarding the location and type of the connection between the component corresponding to the row and the component corresponding to the column of the entry (i.e. topology). Note that each entry is a binary number, which compactly stores all the required information.

The partitioning module takes the DSMs of the two aircraft and produces a 'comparison matrix', $\mathbf{CR}^{(\tau)}$, for each class of component, τ (which could be wing, fuselage, engine, and so forth). In this matrix, the rows correspond to the components of class τ in aircraft a and the columns to those in aircraft b. An entry of one in this matrix indicates that the components in the corresponding row and column will be sent for more detailed similarity detection, whereas an entry of zero indicates that it will not (and hence is considered to be too dissimilar for any design re-use to be possible).

First, information on components of the same class, $C^{(\tau)} \subseteq C$, for each aircraft is organised together in 'class-connection' matrices, denoted by $\mathbf{T}^{(\tau)}$. The size of $\mathbf{T}^{(\tau)}$ is $n \times 3 \times n^{(\tau)}$, where $n^{(\tau)} \leq n$ refers to the number of components of class τ in the specific aircraft. Now, let $m \subseteq k$ (see Equation 1) be a set of size $n^{(\tau)}$, that contains the original DSM indices of the components in $C^{(\tau)}$. Then, for a component $c_p^{(\tau)} \in C^{(\tau)}$ (with

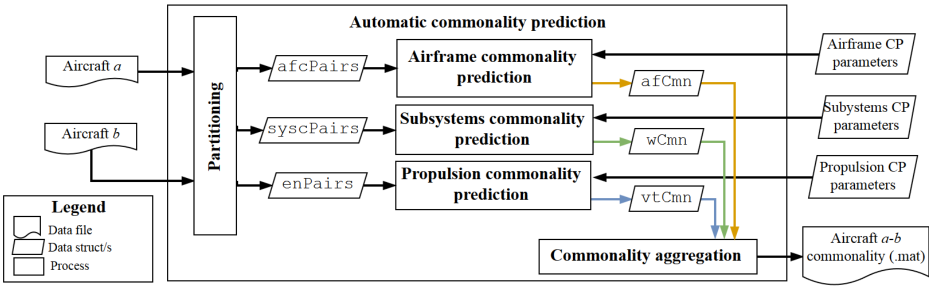


Fig. 2 Automatic commonality prediction overview.

$p \in \{1, 2, ..., n^{(\tau)}\}$ – i.e. p maps to the original indices m), let the columns of $\mathbf{T}^{(\tau)}$ be defined as follows:

$$\begin{aligned} \mathbf{T}^{(\tau)}(\{1,...,n\},1,p) &= \mathbf{D}(\{1,...,n\},1); \\ \mathbf{T}^{(\tau)}(\{1,...,n\},2,p) &= \mathbf{D}(\{1,...,n\},m(p)); \\ \mathbf{T}^{(\tau)}(\{1,...,n\},3,p) &= \mathbf{D}(m(p),\{1,...,n\})^T. \end{aligned} \quad (2)$$

Therefore, the first column of $\mathbf{T}^{(\tau)}$, for component $c_p^{(\tau)}$, lists all the components in the specific aircraft. The second column contains information on the connections of these components, relative to component $c_p^{(\tau)}$. Finally, the third column contains information on these same connections, but now relative to the components attached to component $c_p^{(\tau)}$.

$\mathbf{T}^{(\tau)}$ is used in different ways, depending on the component class under consideration. All the fuselages and all wings of the one input aircraft will be compared with those of the other aircraft, regardless of the results in $\mathbf{T}^{(\tau)}$. Rather, in these cases, $\mathbf{T}^{(\tau)}$ is used, along with the object model, during detailed commonality prediction to determine if sub-segments of the fuselages and wings have the same types of components attached to them at the same locations. For all the other categories of components, the algorithm presented in Figure 3 is run to determine whether the components of the same class should/should not be compared across the two aircraft. This algorithm determines whether component $c_p^{(a)}$ have the same number and type of connections with other components as $c_p^{(b)}$. If this is not the case, the comparison matrix entry corresponding to $p^{(a)}$ and $p^{(b)}$ ($\mathbf{CR}^{(\tau)}(p^{(a)}, p^{(b)})$) is set to zero, which means that these components are too dissimilar to be considered for commonality. The reason for this is that, if airframe components of the same class across two aircraft are attached 1) to a different number of other components, 2) with different types of attachment mechanisms, or 3) at different locations, the structural considerations and aerodynamic interference characteristics would usually be so different that it would be unreasonable to attempt to make them common. This is different for wings and fuselages, which are usually much larger than the other airframe components and can have subsegments common to another aircraft.

```
input  : Aircraft a category-connection matrix, T^(a)(τ); Aircraft b
         category-connection matrix, T^(b)(τ).
output: CR^(τ) – category τ component comparison matrix.
n^(a),(τ) ← length of T^(a)(τ)[1, 1, ..];
n^(b)(τ) ← length of T^(b)(τ)[1, 1, ..];
for p^(a) ← 1 to n1^(a)(τ) do
    for p^(b) ← 1 to n^(b)(τ) do
        Remove rows in T^(a)(τ) where T^(a)(τ)[.., 2, p^(a)] = 0;
        Remove rows in T^(b)(τ) where T^(b)(τ)[.., 2, p^(b)] = 0;
        Sort the rows in T^(a)(τ), such that the entries in
         T^(a)(τ)[.., 1, p^(a)] are in numerical order;
        Sort the rows in T^(b)(τ), such that the entries in
         T^(b)(τ)[.., 1, p^(b)] are in numerical order;
        Round down the values in T^(a)(τ)[.., 1, p^(a)];
        Round down the values in T^(b)(τ)[.., 1, p^(b)];
        if T^(a)(τ)[.., .., p^(a)] = T^(b)(τ)[.., .., p^(b)] then
            // Components to be sent for detailed
               comparison
            CR^(τ)[p^(a), p^(b)] ← 1;
        else
            // Components too different to be compared
            CR^(τ)[p^(a), p^(b)] ← 0;
        end
    end
end
```

Fig. 3 Algorithm: creating a comparison matrix.

3.2 Commonality Prediction Modules

There are three commonality modules – one for the airframes, one for the subsystems, and the other for propulsion. Most of the discussion in this text revolves around the subsystems module, although brief descriptions of the other two are provided. Each module takes the appropriate class-comparison matrices as input, along with objects of the relevant components. These objects are subclasses of the aircraft class and include wings, fuselages, and so forth.

For each component-pair compared, the modules find the mass of the two components that can be considered common. A predicted 'mass-commonality' score is then calculated (for the combination of component i from Aircraft a and component j from Aircraft b) as follows:

$$\Omega_m^{(i,j)} = \frac{m_{cm_{i,j}}}{m_{tot_{i,j}}} = \frac{2m_{cm}}{m_i^{(a)} + m_j^{(b)}}, \tag{3}$$

where m_{cm} is the sum of the masses of sub segments of a component in one of the aircraft that are found to be similar enough to corresponding sub segments in the other aircraft, such that they can be considered common. Note that it will be likely that the masses of two similar components (candidates for commonality) will usually be slightly different. This difference is assigned to be non-common and not included in m_{cm}. The minimum mass of the two common sub-segments is therefore the assigned common mass. The average of the masses of the common subs-segments could also have been taken, but this would not have allowed the difference in mass to be accounted for as 'additional redesign effort'. In other words, if the average was taken, it could appear that two baseline-descendant pairs have similar merit in terms of commonality. However, because one may have a higher difference in mass for a common sub-segment than the other, taking the average will 'hide' that it may actually be less desirable.

A cost commonality score can also be formulated, in a similar fashion as in Equation 3, as follows:

$$\Omega_c^{(i,j)} = \frac{c_{cm_{i,j}}}{c_{tot_{i,j}}} = \frac{2c_{cm}}{c_i^{(a)} + c_j^{(b)}}. \tag{4}$$

This requires a cost model that can provide estimates of the cost of individual components and their sub-segments. Should such a cost model not be available, the masses of the different components could be weighted by user-defined factors to reflect the relative differences in the 'effort' of producing them.

Each module is described separately below.

3.2.1 Airframe

The airframe commonality prediction module takes as input the objects of the fuselages, wings, empennage surfaces, nacelles, and undercarriages, along with their respective comparison matrices as input. Each of these component categories have a dedicated sub-module in which commonality with components of the same class in the other input aircraft is sought.

In each sub-module, the geometry, mass, and other distributions of the components are discretised. Several algorithms then compare these distributions for both aircraft to identify subsegments of the components that can be considered common across the two aircraft.

For fuselages and nacelles (objects of class 'body'), this involved posing the comparison exercise as a longest common subsequence (LCS) problem. Algorithms were developed to solve this problem of which more information can be obtained in Ref. [3]. The algorithms identify common sub-segments across the fuselages/nacelles.

For wings, a simple multi-objective optimization problem was formulated, in which it is aimed to find wingtip-extensions and/or roots-inserts for the longer span wing, such that the difference in surface area and chord-length between the two wings are minimized. Once the tip-extensions and root-inserts are found they are set to be non-common. The remaining wing structure (of the longer wing) is then compared with the shorter wing to determine where chord extensions are needed. Finally, the geometries of the fixed leading- and trailing-edges, high-lift devices, and ailerons are compared to determine if they could be made common. These techniques are also described in more detail in Ref. [3].

Only the planform areas for empennage surfaces (that have a topology similar to the other aircraft) are compared to determine whether they could be made common. To be labelled common, the difference in area must be within a user-specified tolerance.

For undercarriage pairs that have the same layout (as checked for by the partitioning module) the lengths and number of wheels are compared. If these are within a user-specified tolerance, the undercarriages of the two aircraft are assigned to be common.

3.2.2 Subsystems

The system commonality prediction module consists of several sub-modules – one for each of the ATA airframe systems classifications. The operation of these modules are similar however. Each receives the object descriptions of a selected ATA subsystem of the two aircraft as input, together with the component class-comparison matrices obtained from the partitioning module for all the categories of components in the particular subsystem. For each component pair of the same class, the partitioning module checked whether the type (e.g. actuator, compressor, heat exchanger, etc.) is the same and whether the connections to that component are the same, in terms of the number and type of connections (e.g. electrical, pneumatic, and so forth). If these matched for the pair of components, they would have been sent to the relevant ATA subsystem commonality prediction module.

The input pair of components then needs to be compared in more detail to determine the degree to which there is commonality. There are two options i) if components are standard or 'of-the-shelf' their id's (assigned to them by the user) are used to decide if they are the same. If the id's match, the commonality is assigned to be 1. If not, it is assigned to be 0.

Else, if the components are 'rubberised' (i.e. they are scaled parametrically), their characteristics are compared to decide whether they should be common. This is performed by comparing the mass and volume (required to house them in the airframe) of the two components, along with other salient parameters. These parameters could include information for a specific type of component, such as compression ratio for compressors, expansion ratios for turbines, operating pressure in hydraulic actuators, and so forth. If these, along with the mass and volume, are within user-specified tolerances, the component is assigned a commonality score of 1 (i.e. it is the same component). Even if the components are determined to be fully common, should they be in different parts of the airframe the airframe-system integration would require additional redesign effort. This was accounted for by reducing the commonality score through subtracting a user-defined penalty factor (which should be between 0 and 1.), if the components are found to be in different locations. To do this, a 'zone location' attribute was added to the component class description. Each component object therefore has information that specifies in which zone it is located in the aircraft. Figure 4 shows two examples of how zones could be assigned to different types of airframes. As an example, it is shown in this figures that the generators are in the nacelle zones (Z5) and the ECS (environmental control system) packs are in Z2, for the under-wing configuration, and Z3 for the T-tail. In this case, all components in the ECS packs will be penalised, since they are in different zones.

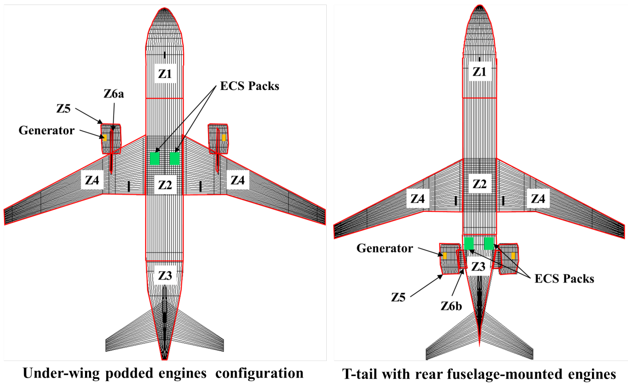


Fig. 4 Airframe zone segmentation for two different aircraft configurations.

Once the commonality scores for the components are calculated, they are combined to provide overall subsystems mass and cost commonality scores, with the use of equations 3 and 4. This information is then dispatched, to the commonality aggregation module.

3.2.3 Propulsion

The propulsion commonality prediction module simply compares the specifications of the engines of the two aircraft. These specifications could include thrust, bypass-ratio, fan and overall pressure ratios, and so forth. If these are within user-specified tolerances, the engines will be assigned to be common. Note that, if the type (turbofan, open-rotor, etc.) is different, the airframe partitioning module would have indicated that no commonality can be achieved for the propulsion. Similarly, if a quad-engined aircraft is compared with a twin, the airframe partitioning module would assign the mass of two of the engines of the quad to be non-common.

3.3 Aggregation

To calculate the overall airframe commonality, all the common masses (or costs) for the different components, as calculated with the above methods, are simply summed and then divided by the total mass (or cost) of the two airframes.

It is vital to appreciate, however, that the resulting airframe commonality scores are only meaningful for descendants compared with the *same* baseline (or baselines compared with the *same* descendant). Therefore, the expected overall 'benefit' that the commonality provides must be articulated in such a way that the merit of different baseline-descendant pairs can be compared. There are two ways to do this, which are as follows:

- The non-common baseline-descendant pair mass (cost), for all the pairs in a study, can be divided by the maximum baseline-descendant pair total mass (cost) found. This provides a number between 0 and 1 that captures the relative difficulty across all the pairs in a study.
- The cost of common components in the descendant can be reduced, using an appropriate cost model (such as, for example, presented by Markish [16]). The resulting total costs of the descendants can then be used as the comparative measure.

The commonality predictions methods provided in this section work well for aircraft with dissimilar airframe configurations, as will be demonstrated next.

4 Demonstration

To demonstrate how the techniques could be used in early design stage aircraft evolvability exploration, a design study for a notional short-range (2,700 nmi), 150-passenger airliner was devised. The goal of the study was to populate both the near-future and far-future entry-into-service (EIS) design spaces with potential designs, upon which the commonality prediction method could be applied. For the near-future EIS, the clock was wound back to 2015 and, for the far-future, the EIS was set to be within the 2025 to 2035 timeframe.

4.1 Aircraft Architectures

Several combinations of conventional and unconventional configurations, subsystems architectures, propulsion, and airframe technologies were considered for this study. The airframe configuration-technology combinations (CTCs) are depicted in Figure 5. For subsystems architectures, the Environmental Control System (ECS) and Ice Protection System (IPS) were considered. A set of four architectures were created as shown in Table 1.

Table 1 Subsystems Architectures

Architecture	ECS	IPS
A1	Conventional	Conventional
A2	Conventional	Electrical
A3	Electrical	Conventional
A4	Electrical	Electrical

4.2 Scenarios

A detailed scenario planning and technology road-mapping exercise was documented by Northrop Grumman for their N+3 proposal,

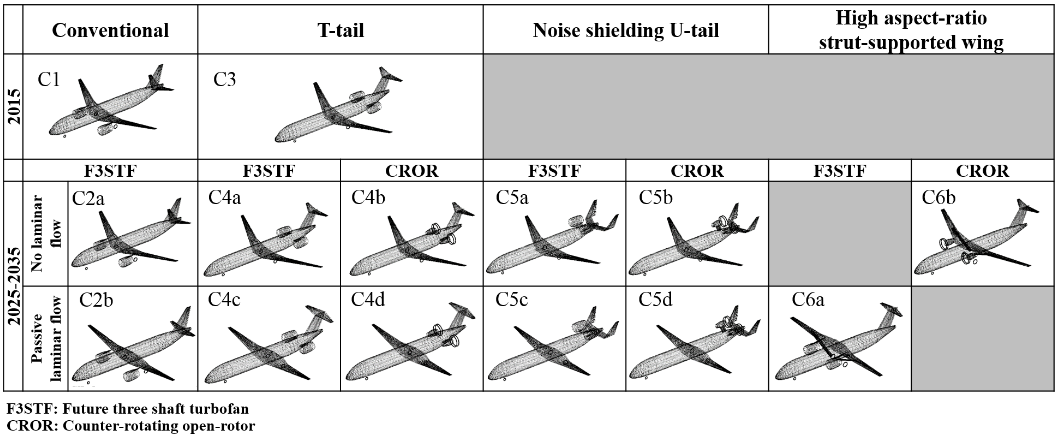


Fig. 5 Configuration-technology combinations (CTCs) selected for the demonstration case study.

namely the “Subsonic Fixed Wing Silent Efficient Low-Emissions Commercial Transport” (SELECT) [17]. In that study, three main possible scenarios for the 2035 timeframe were identified. These were modified for the current research and are briefly described below:

- Scenario 1: Bright Bold Tomorrow (BBT). A strong global economy prevails and there is increased demand for comfort in aeroplanes and operations from smaller airports (i.e. shorter runways). Competition amongst airlines force them to look for ways to cut operating cost.
- Scenario 2: Not in My Backyard (NiMBY). The global economy is growing, albeit slower than in BBT. Fast-growing populations around airports are becoming increasingly intolerant to noise and NOx emissions and the focus in this scenario is therefore on reducing these.
- Scenario 3: King Carbon (KC). Deleterious effects of climate change are starting to take its toll and air transportation is severely affected by the ensuing rise in fuel prices. The focus is therefore mainly on improving fuel efficiency, but also to ensure overall lower operating costs.

For the current study, three far-future scenarios were considered, i.e. ‘BBT 2035’, ‘NiMBY 2035’, and ‘KC 2035’, whereas only one near-future scenario was considered, namely ‘BBT 2015’. In order to determine the relative value attributed to the different designs by stakeholders in each scenario, a utility function was devised in terms of a simple weighted sum, as follows:

$$u = w_F S_F + w_N S_N + w_C S_C + w_O S_O \qquad (5)$$

Here, u is the utility for a selected design, which should be between 0 (not acceptable) and 1 (the best available). If a utility score was calculated to be equal to zero for a scenario, the associated aircraft was not considered to be an option in that scenario. The coefficients w_F, w_N, w_C, and w_O are weighting factors for fuel burn, noise, passenger comfort, and operating benefits (improved maintenance, reliability, and safety), such that

$$w_F + w_N + w_C + w_O = 1 \qquad (6)$$

The values for these are different in each scenario, where they reflect the relative importance of the aspects they weigh in the selected scenario. The values selected for the current research are hypothetical and for demonstration purposes only. They are listed in Table 2, for each scenario, along with the field-length (FL) constraint. S_F, S_N, S_F, and S_O are ‘System Effectiveness Ratings’ (SERs) (using the terminology of Ref. [17]) for fuel burn, noise, passenger comfort, and operating benefits, respectively. As with utility, the values for these should be between 0 (not acceptable) and 1 (the best available) for the associated design to be considered in a selected scenario. For fuel burn, the SER for a selected

Table 2 Scenario utility calculation weighting factors and constraints.

	BBT 2015	BBT 2035	KC 2035	NIMBY 2035
w_F	0.50	0.20	0.65	0.10
w_N	0.50	0.25	0	0.80
w_C	0	0.25	0	0.10
w_O	0	0.30	0.35	0
FL (m)	2080	1580	1830	1830

design option is calculated as follows:

$$S_F = \begin{cases} \frac{\Delta BF - \Delta BF_{min}}{\Delta BF_{max} - \Delta BF_{min}} & \text{if } \Delta BF > 0 \\ 0 & \text{else} \end{cases} \quad (7)$$

where $\Delta BF = BF_{A320} - BF$, BF is the predicted block-fuel burned by the selected design, and BF_{A320} is the block-fuel burned by the A320 on a nominal design mission. ΔBF_{min} is the minimum positive block-fuel reduction amongst all the designs considered in the study, whereas ΔBF_{max} is the maximum attained. The SER for noise was calculated with the following equation:

$$S_N = \begin{cases} \frac{\Delta N - \Delta N_{min}}{\Delta N_{max} - \Delta N_{min}} & \text{if } \Delta N > 0 \\ 0 & \text{else} \end{cases} \quad (8)$$

where $\Delta N = EPNL_{Limit} - EPNL$, and $EPNL$ is the cumulative 'effective perceived noise level' for each aircraft. $EPNL_{Limit}$ is the calculated cumulative noise limit. ΔN_{min} is the minimum positive noise reduction found amongst all the designs considered, whereas ΔN_{max} is the maximum. The SER for passenger comfort was calculated with the following expression:

$$S_C = \frac{C_1 + C_2}{2} \quad (9)$$

where

$$C_1 = \begin{cases} 1 & \text{if } \Delta M_{Cruise} > 0.75 \\ 0.001 & \text{if } \Delta M_{Cruise} < 0.75, \text{scen} \neq \text{BBT} \\ 0 & \text{else} \end{cases} \quad (10)$$

and

$$C_2 = \begin{cases} 1 & \text{if } W_{Fus} > 4 \text{ m} \\ 0 & \text{else} \end{cases} \quad (11)$$

M_{Cruise} is the cruise Mach number and W_{Fus} is the width of the fuselage. This indicates that much emphasis is placed on convenience (speed) and physical comfort (large cabin space). Finally, the SER for operating benefits, S_O, was simply set to 0.3, 0.8, 0.6, and 1 for architectures A1, A2, A3, and A4 respectively (see Table 2).

If any of these SERs for a design were calculated to be equal to zero for a particular scenario, the design was not considered as an option in that scenario. In addition, if a design did not meet the takeoff and landing field length constraint for a scenario, it was also removed from consideration in that scenarios.

4.3 Modelling and Simulation

For modelling and simulation of the different combinations of airframes, subsystems and propulsion, in-house design software tools, 'AirCADia Architect' and 'AirCADia Explorer', and 'AirCADia Aircraft Geometry', were employed. AirCADia Architect is a subsystems architecting tool, which is used to define different architectural views (e.g. requirements, functional, and logical). AirCADia Explorer is a model-based design environment for designing complex products, which can dynamically configure computational workflows. Details of the methods implemented in these tools are available in Refs [15] and [18]. Finally, AirCADia Aircraft Geometry [19] is a fast 3D aircraft geometry parametrisation tool.

For estimating performance of different aircraft configurations and subsystems architectures, various publicly available computational models and tools were employed. In particular, the Flight Optimization System (FLOPS), developed by McCullers [20], was used for aircraft and mission performance evaluation. FLOPS aircraft sizing models are limited to conventional subsystems architectures and therefore models for non-conventional (more electrical) subsystems architectures were developed, based on several sources. These models estimate the mass and the required engine power off-takes (shaft power and bleed-air) in order to determine the effects of the subsystems architectures at aircraft level. Details on the models employed for the subsystems, along with the relevant references, can be viewed in Riaz [21]. For cost and noise, the methods in Refs [16] and [22] were used, respectively. The noise model had to be adapted to predict open rotor noise. For further details on this, along with more information on the general modelling of the airframe and propulsion, the reader is directed to Ref. [3].

A full-factorial Design of Experiment (DoE) study was then created in AirCADia Explorer to evaluate all the different combinations of aircraft configurations and subsystems architectures. In addition to the different configurations and architectures, the wing aspect ratio, wing area, fuselage width, and others were also varied in the DoE. For each combination of input variables (i.e. each design), the utility and cost were evaluated.

The proposed commonality prediction methods were implemented in several MATLAB® scripts. These take airframe configuration objects (with geometry) and subsystems architectural information (in DSM format), and produce the commonality scores for each baseline-descendant pair considered.

4.4 Commonality Results

The commonality prediction method was executed for pairwise combinations of 2015 and 2025-2035 aircraft. For the case study demonstration, a total number of 50 baseline aircraft (the top 25 configurations from C1 and C3 were considered, by adjusting a Fuzzy-Pareto number [23]). However, all the configurations in the 2025-2035 timeframe (i.e. 1,444) and all four subsystem architectures were considered as potential descendant aircraft, which resulted in 5,776 (1444×4) possible aircraft. Therefore, the commonality prediction method was executed a total number of 288,800 times (50 baselines $\times$ 5,776 possible descendants). The average computational time was calculated to be 2.44 on a desktop PC with an Intel Core i7-4770 CPU @ 3.40 GHz processor.

Once the commonality scores of all the (baseline-descendant) combinations are available, several different ways can be employed to support evolvability-related decision-making. One way is to apply set-based design techniques (as demonstrated in Ref. [3]) to filter out designs that are dominated by more desirable designs. Here, however, it will be shown how the commonality results could be exploited to perform interactive evolvability exploration. For instance, Figure 6 shows the results of IPS and ECS commonality for a selected baseline aircraft with the far-future aircraft for all three scenarios. Each point in Figure 6 represents an aircraft, i.e. a combination of configurations and subsystems architectures. The selected baseline aircraft (B1) is represented by black point in plot (a), whereas the commonality scores of the descendant aircraft with this baseline are shown on the x-axis of plots (b), (c), and (d). The different colours in plots (b), (c), and (d) represent the different subsystems architectures. It can be observed from Figure 6, that the selected baseline aircraft (B1) performs better in BBT 2035 and NiMBY 2035, but that the relative utility in KC2035 is significantly lower.

The proposed framework also enables one to visualize the commonality by means of geometry and architectural layout renderings. For instance, Figure 7 shows the commonality results separately for the selected baseline aircraft (B1). Figure 7 (a) shows the airframe commonality results, where the same colour across the two airframes represents commonality and the white colour represents dissimilarity. Similarly, Figure 7 (b) shows the subsystems architecture commonality results, where components highlighted by the coloured squares represent common components.

5 Conclusions

The framework provides a powerful means with which to explore evolvability in aircraft at the early stages of design. In particular, it enables commonality assessment across airframes and subsystems that could have radically dissimilar configurations, in addition to having components

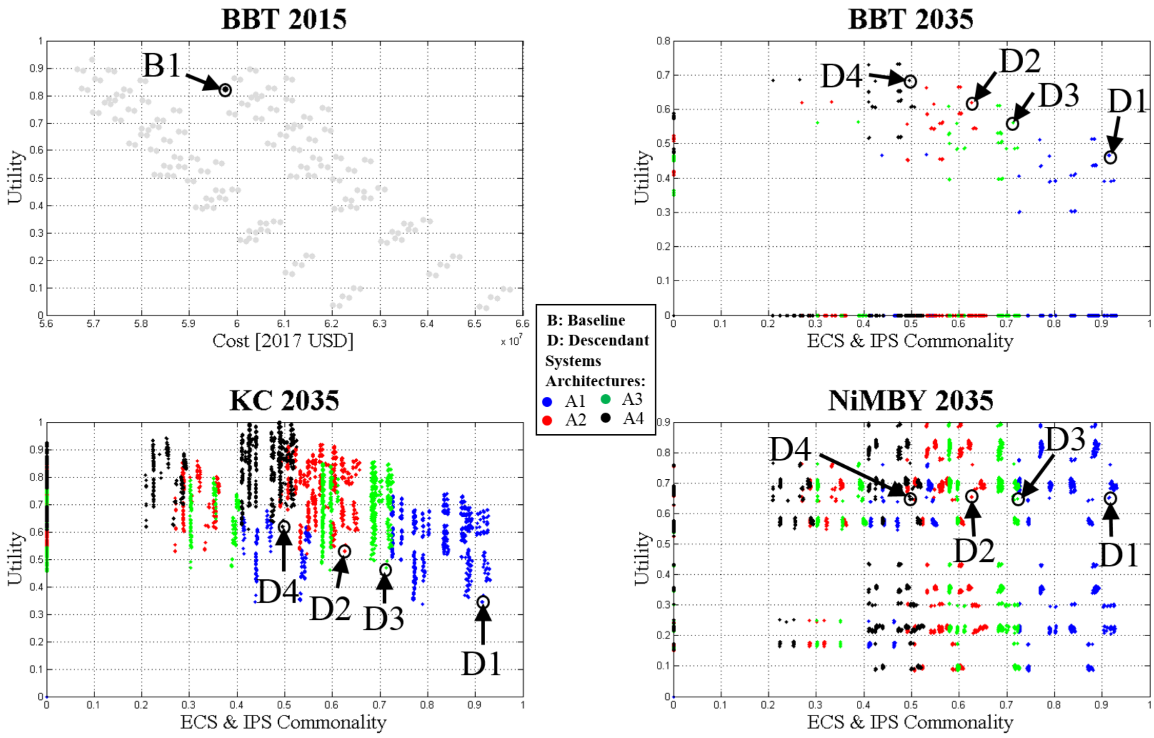
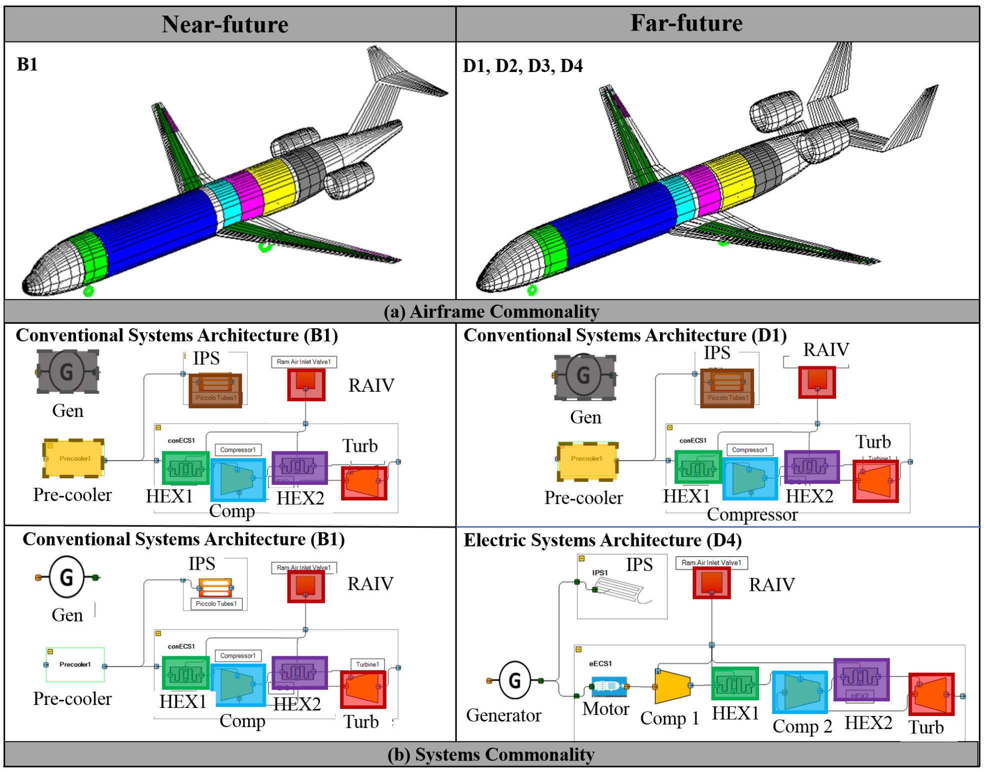


Fig. 6 Multi-attribute tradespaces showing commonality results with a Selected Baseline (B1).



Legend:
Comp: Compressor   HEX: Heat Exchanger   RAIV: Ram-Air Inlet Valve   Fully common
Gen: Generator   IPS: Ice Protection System   Turb: Turbine   Common, but extra integration effort
Components/segments with corresponding highlighted colours across the two pairs of airframes/systems are common.

Fig. 7 Visual renderings of the airframe and subsystems commonality.

that have possible different scales. The systems commonality prediction methods are generic and could conceivably be applied for most types of aircraft subsystems.

The framework should also be easily integrated into existing design tools, but some effort would be required to implement the knowledge base required for the commonality assessment. For example, specialists would need to be consulted to elicit the required tolerances within which components/segments could be considered 'similar'.

By removing the need to pre-specify commonality, the framework allows the near- and far-future design spaces to be sampled separately. This could enable savings in terms of computational cost in certain cases (see Ref. [3] for more details).

Finally, future work would involve testing the framework for more aircraft subsystems and improving the computational efficiency of the techniques, amongst others.

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