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ENHANCING THE EXPLORATION OF AIRCRAFT CHANGEABILITY DURING CONCEPTUAL DESIGN

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Abstract

Changeability is a characteristic of a system that may allow it to be changed in an affordable manner to maintain value, despite changing external conditions. In this paper, a framework is presented that employs concepts from Multi-Attribute Tradespace Exploration and Epoch-Era Analysis, together with interactive commonality identification, to enable aircraft designers to explore the changeability of aircraft that have different top-level configurations and to interactively identify where and how much changeability should be introduced in their designs during conceptual design. The frame-work is demonstrated by illustrating how the changeability of a short-range, environmentally friendly passenger aircraft can be explored.

1 Introduction

An important way for an aircraft to remain relevant in a changing world is by being 'changeable' itself. In other words, it should be designed such that it may be changed swiftly and affordably, should the need arise. The word 'changeability' is an umbrella term for many 'change-type ilities', such as 'flexibility', 'adaptability' and others [1]. For this paper, changeability will be considered to be synonymous with 'evolvability' – the extent to which the design of a system can be "inherited and changed across generations (over time)" [1]. During conceptual design, it is essential that the design space be explored thoroughly to determine how different designs will cope with changing socio-economic conditions, competitor activity, and technology development. Previous work in changeability exploration in aircraft design usually only considers exploring pre-determined top-level configurations (i.e. major components layouts) and pre-specified transition paths (e.g. upgrading the engines) – see for example [2].

The aim of the work was therefore to develop a framework that consists of procedures and enabling tools that could ensure: 1) that multiple different configurations (architectures) could be explored simultaneously and 2) that interactive identification of transition paths could take place, rather than specifying these in advance.

The paper is organized as follows: Section 2 contains a brief overview of changeability and related concepts and Section 3 shows how the combination of two well-known design space exploration techniques, namely 'Multi-Attribute Tradespace Exploration' (MATE) and 'Epoch-Era Analysis' (EEA) could be applied to aircraft changeability investigation. Section 4 is a description of the proposed framework; and, in Section 5, the framework is demonstrated with the changeability exploration of an environmentally friendly, short-range passenger aircraft. Finally, conclusions are drawn and future work is outlined in Section 6.

2 Overview of changeability concepts

2.1 What is Changeability?

Changeability is a particular way of dealing with uncertainty [3]. Essentially, it provides two-fold value to the stakeholders of the system in the presence of uncertainty [4]: 1) value is provided, since the system maintains (or increases) its performance in changing circumstances, and 2) value arises because the changeable system provides the stakeholders with options. Unfortunately, this value comes at a cost, which often manifests as an extended and more expensive development period of the first generation of the system. The changeable system also usually does not perform optimally in any single set of circumstances, as compared with non-changeable systems.

To be able to change, the system must have a 'change mechanism'. A change mechanism refers simply to *how* the system is changed [3]. For example, to decrease fuel-burn, an existing airframe could be upgraded with a new, more efficient engine. The process of upgrading the aircraft is the change mechanism. Designing for changeability includes 1) finding which change mechanisms are required and 2) to make these more affordable. Several 'changeability principles' can be employed for this purpose, including 'modularity', 'simplicity', scalability, and so forth. A comprehensive description of these is provided in [5]. Finally, note that a change mechanism also has a cost associated with it. This is the time, effort, and monetary expense needed to perform the change.

2.2 Changeability exploration

Changeability exploration refers to exploring the design space to find designs that could maintain value under changing circumstances by being changed. One method to do this is Multi-Attribute Tradespace Exploration (MATE) together with Epoch-Era Analysis (EEA) (see, for example [4]). A Multi-Attribute Tradespace (MAT) is a plot of utility and cost of the system [6]. Utility is a variable, usually ranging in value from 0 to 1, which represents the weighted normalized sum of system attributes that are of importance to the stakeholders. The cost is determined by the design parameters, and could involve, for example, the investment required to develop the system, or the lifecycle cost. During conceptual design, the MAT is populated with multiple potential design points, where each point represents the utility and cost of a specific design.

Epoch-Era Analysis is a way of exploring how circumstances affecting the system can change over time and how the different designs respond to these changes [4]. An 'era' represents the lifetime of the system and consists of several 'epochs' strung together. An epoch is a time-period within an era where stakeholder preferences, technological maturity, and environmental conditions are assumed to remain constant. Every epoch can subsequently be represented by its own MAT. Change mechanisms form allowable 'transition paths' between different design points across sequential epochs. Therefore, if designs have transition paths to other designs in the subsequent epoch available, they could be changed across the 'epoch shift' (i.e. the progression of time with an associated change in circumstances). However, in the case of designs with multiple transition paths, only one of the paths will actually be exploited. This means that a strategy is required to select the transition path during the epoch shift [4]. This will be referred to in this paper as a 'change implementation strategy'. Such a strategy could be, for example, to choose the path that will provide the highest utility of the design in the subsequent epoch, regardless of the cost, or choose the path that will produce the design with the lowest cost, at an acceptable utility.

Most literature on aircraft changeability, although excellent, usually only enable a single top-level aircraft configuration to be explored (see for example [2]). To improve on this, a more comprehensive exploration is needed where different configurations can be investigated simultaneously. MATE with EEA enables designs with completely different architectures to be explored simultaneously, and the combination of these was therefore selected for the current work as the analysis method.

Also, in most previous work on changeability exploration, transition paths are specified in advance. Several notable exceptions exist, such as [7], which usually employ 'Design Structure Matrices' (DSMs) that will highlight components that are most likely to change, and therefore to be made modular. Unfortunately, these are not always readily applicable to the parametric design tools usually employed during conceptual aircraft design. What seems to be needed is a method to enable the designer to interactively visualize and identify possible transition paths (involving both changing components, as well as design parameters), and trade off commonality with the potential transition paths.

2.3 Interactive commonality identification

A field that is strongly related to changeability is that of product family and product platform design. A major theme in the product family literature is identifying commonality between products aimed at meeting the requirements of different customers. To relate this to changeability, commonality would refer to the parameters and components that do not need to change with time. Subsequently, by identifying commonality, the designer implicitly also identifies where transition paths are required. Certain product family methods to identify commonality can therefore be adapted for use in changeability. Of particular interest here are those methods that enable the designer to identify commonality in a visual and interactive manner, such as in [8] and [9]. In [9] it is shown how the designer can interactively select design parameters/modules to be made common amongst the product variants, while simultaneously observing the effect in the objective space.

3 Applying MATE and EEA to aircraft changeability studies

In this section it will be shown how Multi-Attribute Tradespaces could be set up for aircraft, which will enable Multi-Attribute Tradespace Analysis and Epoch Analysis to be performed to analyze and enhance aircraft changeability. The term ‘scenario’ will be used here instead of ‘epoch’. A scenario will therefore refer to a period where external conditions are assumed to remain constant. Also, because the changeability under discussion is evolvability, the word ‘generation’ will be employed to refer to designs in successive time periods. Each time period will therefore refer to a generation.

Fig. 1 shows two MATs – the one on the left represents a possible first generation scenario, whereas the one on the right represents a possible second generation scenario. The design represented by the orange dot on the left is a new design for the first generation. The utility of this design represents how well it is expected to meet the particular combination of requirements of the scenario associated with the first generation. The cost (to the manufacturer) of one aircraft of this design comprises the Research, Development, Test, and Evaluation (RDT&E) cost per aircraft, plus the first-unit manufacturing cost. There are three options an original equipment manufacturer (OEM) has for the subsequent generation designs: completely re-use the first-generation design (orange dot on the right in Fig. 1), design a completely new aircraft (blue dot), or upgrade the first-generation design (green dot). The first option would only be possible if the utility of the first-generation design is still above zero in the second generation timeframe. The cost in this case will only comprise the unit manufacturing cost, which will be less than the first-unit manufacturing cost (when adjusting for inflation). Cost will therefore be low, but the utility probably also. If, on the other hand, the OEM opts for the second option, the full RDT&E cost for a new aircraft, plus first-unit manufacturing cost, will be incurred. The cost will be high, but requirements may possibly be exceedingly well met.

A more likely course of action would be the third option, which is a compromise. In this case, changes are made to the design that enable it to

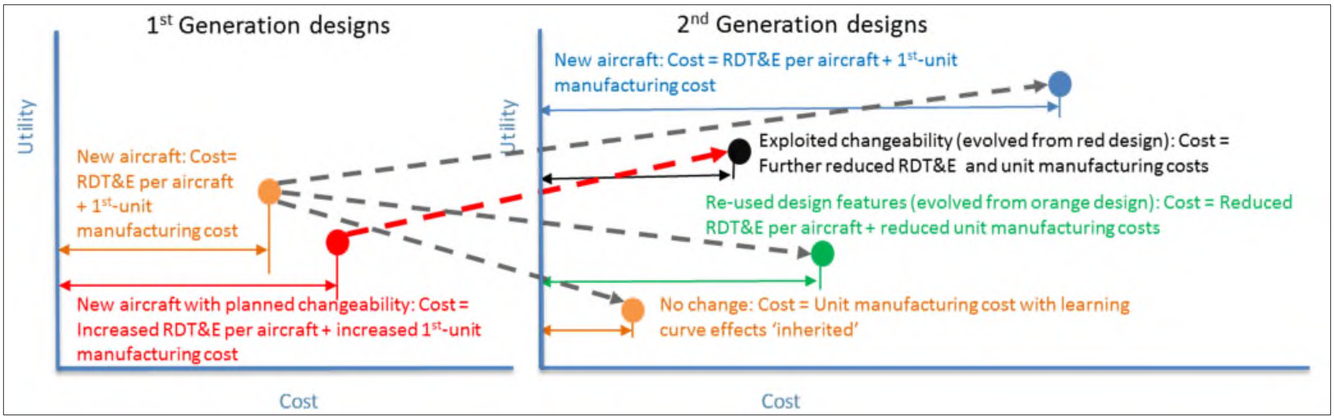

Fig. 1: Multi-attribute tradespaces for aircraft evolution. The arrows indicate options and not necessarily transition paths.

better meet the new requirements at reduced cost. This entails a combination of re-using components that do not need to change and designing new ones where necessary. This provides savings on both RDT&E and manufacturing costs, since only selected components would need to be re-developed. A common example of this is to refit an existing airframe design with new propulsion. However, this strategy usually delivers designs with less performance than what is actually possible with new technologies that have since become available. This is represented by the lower utility of the green dot in Fig. 1 (right).

To enable further savings in the development and manufacturing cost of future generations, the OEM could invest in designing the first generation to be more changeable (i.e. bestow it with planned changeability). Such a course of action would likely entail a higher first-generation RDT&E cost per aircraft and first-unit manufacturing cost and lower utility, as compared with designs with no planned changeability, but may help to increase second-generation utility. This is illustrated with the red and black dots in Fig. 1.

The above constitute fundamental underlying concepts that are employed throughout the framework, which is discussed next.

4 Description of the framework

The framework consists of a step-by-step process, along with enabling techniques that can be employed for each step. A diagram illustrating the steps is shown in Fig. 2.

The basic input to the framework is, inter alia, information on socio-economic and technology trends, competitor activity, and so forth. The output is a set of designs that are most promising in terms of meeting both the current requirements and able to change, at a reasonable cost, to meet future requirements (i.e. the most changeable designs).

Step 1: Scenario identification and development

The objective of this step (Step 1 in Fig. 2) is to identify current and future requirements and use these to create MATs with associated utility definitions for the different possible scenarios.

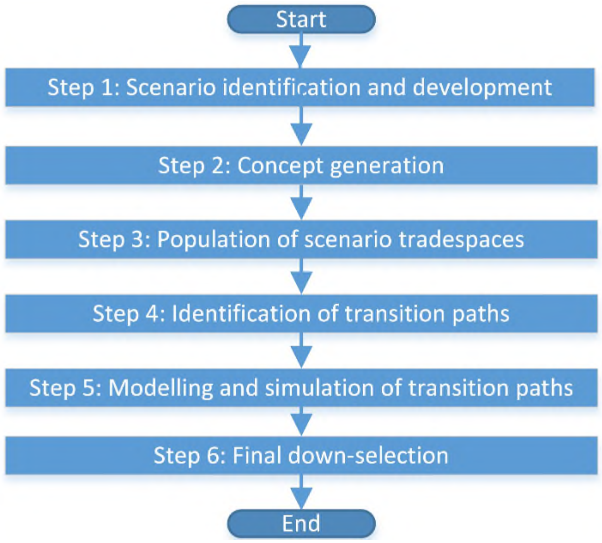

Fig. 2: Steps of the aircraft changeability exploration framework.

The activities in this step will usually fall under the responsibility of the business or technical strategy departments of the OEM. To initiate the process, information is collected on relevant socio-economic trends, tendencies in technology development, future environmental sustainability targets, competitor activity, and so forth. Using this information, utility definitions can be formulated for different possible scenarios for each generation of designs. This means that a set of MATs can be constructed that coincide with each planned entry-into-service (EIS) date for each successive generation. The different MATs for each generation therefore represent the different possible combinations of requirements and conditions that might be prevalent at the time of service entry and during (most of) the lifetime for that generation. This is illustrated in Fig. 3.

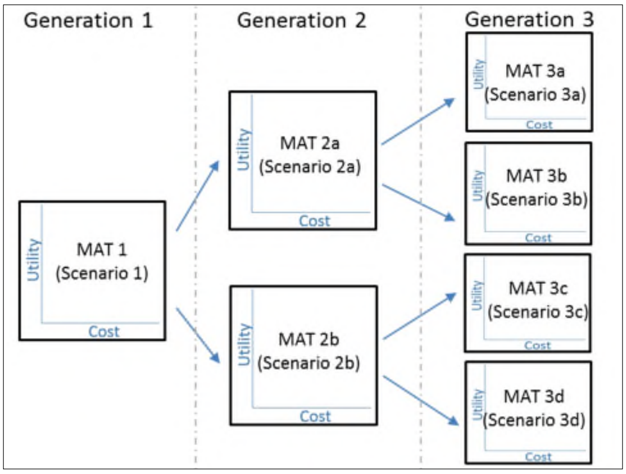

Fig. 3: Aircraft evolution: generations and scenarios.

Consequently, each possible ‘string’ of scenarios (epochs), indicated by the arrows in Fig. 3 forms a possible era for the aircraft.

Finally, change implementation strategies for the different scenarios, which will be dictated by the conditions prevalent to each scenario, should also be formulated in this step.

Step 2: Concept generation

In this step, different concepts, including different top-level configurations and systems architectures, are generated that could potentially meet the requirements of both current and future scenarios. Seemingly ‘inferior’ concepts should not be discarded in this step.

Step 3: Population of scenario tradespaces

Once a set of promising concepts have been identified, modelling of the concepts can commence. After the models are constructed, simulation can proceed in order to populate the MATs with potential solutions. This can be performed with the use of an appropriate enumeration technique, such as optimization or a design-of-experiments (DoE) study. The authors recommend a DoE for changeability/ evolvability, however, since the uncertainty involved may be significant and it may be more appropriate to cover more of the design space by making use of a DoE.

Step 4: Identification of potential transition paths

With the MATs populated, they can be used to identify where transition paths can/should be introduced. This can be done with the following procedure, which is adapted from [8] and [9] (see Section 2.3):

- Based on the change implementation strategies identified for the different scenarios, select a ‘region of interest’ for each different top-level configuration and each systems architecture in each scenario. This will require the MATs of aircraft with different top-level configurations to be viewed separately. The region of interest is the set of designs that will most likely be selected based on the economic conditions for a specific scenario. The selection can be automated, by specifying a minimum utility and maximum cost, or the designer could interactively select the area on the MAT. The advantage of using this (for evolvability) is that it already acts as a filter that could potentially reduce the number of designs that have to be compared.
- Compare the designs on the region of interest, selected across all scenarios and all generations, and find parameters or technologies that are shared. This can be done by making use of multi-dimensional visualization techniques. If only a few scenarios and few parameters/technologies are considered, parallel coordinates may be appropriate.

The result of this process is therefore a reduced set of designs that have some parameters/ components shared and some not. For combinations of parameters/components that cannot be made common (i.e. irreducible sets), two courses of action are possible:

- The first is to look for designs that may have increased commonality, but could have decreased predicted performance. One way of doing this is by going back to the tradespace and increasing the regions of interest. Alternatively, the designer could select the parameter values/components that he/she may want to be shared across scenarios (i.e. to enforce commonality), which will reverse the process and indicate how large the region of interest must be. In this manner, the designer can interactively explore the design space to gain a better understanding of what the tradeoff is between the commonality and changeability of the designs and to find a set of solutions that he/she may deem acceptable.
- The second course of action can be invoked if the increase in the region of interest is not acceptable. In this case, transition paths will have to be formulated to enable transition between the parameters that cannot be made common. This is discussed in Step 5.

Note that this method will usually provide multiple combinations of parameters/ components that could be changed (i.e. multiple transition paths that can achieve the same effect). The designer could choose to investigate all of them, or choose only selected ones, based on domain knowledge. Also, the potential transition paths identified will depend on the sequence in which parameters/components were selected to be made common. Again, the designer may choose to explore different sequences, or select an appropriate one, based on experience.

Step 5: Modelling and simulation of transition paths

In the previous step, combinations of parameters and/or components were identified that require transition paths. This essentially means that a transition is required from one aircraft design to another. In this step, the 'how' of this transition must be addressed. The changeability principles from [5] could prove useful in this step, but domain knowledge is essential. An example could be a required change in span (from the first generation to the second). In this case, two transition paths are possible: design a new wing, or a pre-planned span extension. Both of these will add additional considerations during the design of the first generation aircraft, which could involve, for example, aero-elasticity and stability concerns, amongst others. However, for conceptual design purposes, at least the increase in mass and cost, and the effect on aerodynamics of the transition paths must be reasonably captured. Once the transition paths are identified, they can be modelled, after which another design-of-experiments study should be run to further populate the MATs – now with designs that have planned changeability incorporated.

Step 6: Final down-selection

The goal of the final step is to analyze all the designs and to find those that are most likely to meet both current and future requirements. For this purpose, the change implementation strategies defined in Step 1, as well as changeability metrics (see Section 2) can be applied to find the most valuably changeable designs. Aircraft with dissimilar top-level configurations are now considered together.

5 Framework demonstration: evolvable single-aisle passenger aircraft

In this section, the changeability framework proposed above is applied to find first-generation designs for a short-range, single-aisle passenger aircraft that could be changed 'easily' to second-generation aircraft that would excel in different scenarios that may have diverse and conflicting combinations of requirements regarding environmental friendliness. These include requirements related to fuel-burn, Nitrogen-Oxide (NOx) emissions, noise, and field length. For the purposes of this example, EIS for the first generation will be 2020, whereas the EIS for the second generation will be 2030. The requirements that will not change are the number of passengers (150) and range (2700nm).

Note that the goal of this study was not to design aircraft that would meet future environmental targets, but to illustrate how the framework could be used – the parameter values used are notional only and do not reflect any actual aircraft or technologies.

Step 1: Scenario identification and development

One scenario for the first-generation (2020) and three for the second-generation aircraft (2030) were considered. These were adapted from the scenarios presented by Northrop Grumman for their N+3 study [10]. The scenarios for 2030 are briefly described as follows [10] and [11]:

- "Bright Bold Tomorrow (BBT)" 2030: Field-length requirements are much stricter than for today's aircraft. Also, the OEM would happily pay more to develop aircraft with higher utility.
- "Not in My Back Yard (NiMBY)" 2030: Strict regulations regarding noise and emissions are in place and considered more important than fuel-burn and field length. The OEM would like to find a balance between high utility and high cost.
- "King Carbon (KC)" 2030: Carbon emissions is the prime consideration. Noise and field-length is not considered important. The OEM would like to find designs that have low fuel-burn, but at the lowest cost possible.

The scenario for 2020 was called 'BBT 2020' and had the same weightings as BBT 2030. The utility values could be calculated as follows (adapted from [10]):

$$u = w_F S_F + w_N S_N + w_E S_E + w_{FL} S_{FL} \qquad (1)$$

where w_F, w_N, w_E, and w_{FL} are weighting factors for fuel-burn, noise, emissions and field length, and:

$$S_F = \begin{cases} 0;\ \text{if } F > F_R \\ \dfrac{F_R - F}{(1 - K_F)F_R};\ \text{if } F \leq F_R \text{ and } F > K_F F_R \\ 1;\ \text{if } F \leq K_F F_R \end{cases} \qquad (2)$$

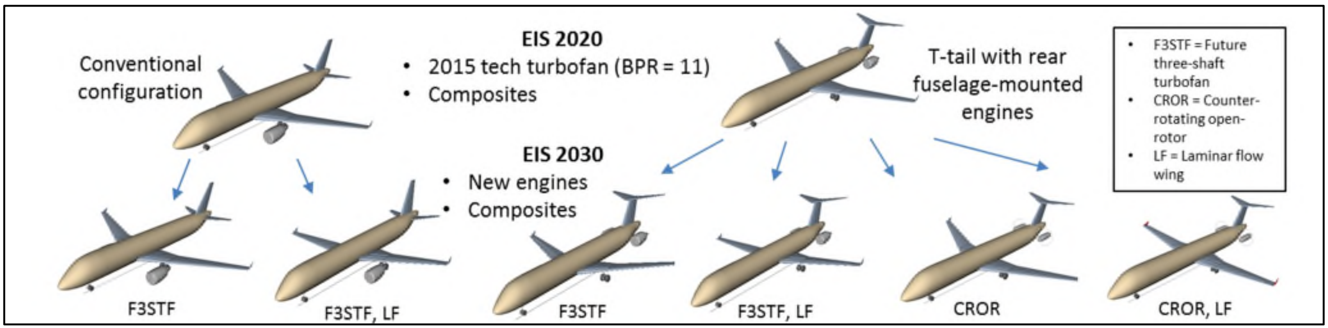

Fig. 4: Concepts generated for 2020 and 2030 EIS (images rendered in PACELAB [17]).

S_F is the "System Effectiveness Ranking" (SER) [10] for fuel-burn. F is the block-fuel per available-seat-mile (ASM) of the design in question [lbm/nm]; F_R is a reference block-fuel per ASM of 0.83 lbm/nm (a typical value for a 1990's technology 2700 nm, single-aisle 150 seat passenger aircraft). K_F represents a specified fraction of block-fuel per ASM, compared with the reference value (for example, if $K_F = 0.3$, it represents a fuel-burn reduction of 70%). Similarly,

$$S_N = \begin{cases} 0;\, if\ N_{S4} - N < 0 \\ \dfrac{N_{S4} - N}{M_N};\, if\ N_{S4} - N \geq 0\ and\ N_{S4} - N < M_N \\ 1;\, if\ N_{S4} - N \geq M_N \end{cases} \quad (3)$$

Here, S_N is the SER for the Effective Perceived Noise Level (EPNL) of the design in question; N is the predicted noise in effective perceived noise decibels (EPNdB) produced by the design in question; N_{S4} is the Federal Aviation Regulation (FAR) Part 36, Section 103 Stage 4 limit on noise [12] for an aircraft with the same mass as that of the design in question [EpNdB]; and M_N is target margin on noise with respect to the FAR Stage 4 limit [EPNdB]. Furthermore,

$$S_E = \begin{cases} 0;\ \text{if } E > E_{C6} \\ \dfrac{E_{C6} - E}{(1 - K_E)E_{C6}};\text{if } E \leq E_{C6} \text{ and } E > K_E E_{c6} \\ 1; \text{if } E \leq K_E E_{C6} \end{cases} \quad (4)$$

Where S_E is the SER for Nitrogen-Oxide emissions; E is the landing-takeoff cycle (LTO) NOx emission index in g/kg of the design in question [13]; E_{C6} is a reference value, based on the Committee on Aviation Environmental Protection's (CAEP) CAEP/6 standard [13]; and K_E represents the fraction of NOx emissions compared with the CAEP/6 standard.

Finally,
$$S_{FL} = \begin{cases} 0; \text{if } BFL > BFL_{req} \\ 1; \text{if } BFL \leq BFL_{req} \end{cases} \quad (5)$$

Where S_{FL} is the SER for balanced field length; BFL is the balanced field-length required by the design in question (maximum of the takeoff or landing balanced field lengths) in ft; and BFL_{req} is the required BFL in a specific scenario [ft].

The values for the weightings, and for K_F, K_E, M_N and BFL_{req} selected are shown in Table 1.

Table 1: Weightings/reference values for the scenarios.

	BBT 2020	**KC 2030**	**NiMBY 2030**	**BBT 2030**
w_F	0.25	0.65	0.1	0.25
K_F	0.5	0.4	0.4	0.4
w_N	0.2	0	0.4	0.2
M_N [EPNdB]	42	71	71	71
w_E	0.25	0.35	0.4	0.25
K_E	0.25	0.2	0.2	0.2
w_{FL}	0.3	0	0.1	0.3
BFL_{req} [ft]	6500	6000	6000	5000

K_F, K_E, and M_N correspond to NASA's N+2 and N+3 targets, summarized in [14].

Step 2: Concept generation

Only two top-level configurations were considered for this study: a 'conventional' layout and a T-tail, with fuselage-mounted engines (see Fig. 4). All the concepts have airframes that are made mostly of composites. The engine technology considered for the 2020 generation aircraft are similar to the newest engines available on today's short range aircraft, with a bypass-ratio (BPR) of 11 and an overall-pressure ratio (OPR) of 40. These will be referred to as 'TF 2020'. Engines considered for the 2030 generation aircraft were future three-shaft turbofans ('F3STF'), with BPR = 18 and OPR = 50, and counter-rotating open-rotor ('CROR') engines with OPR≈36. Laminar flow (LF) wings were also considered for the 2030 aircraft. Finally, two types of flaps were considered: single-slotted (SSF) and triple-slotted (TSF).

Step 3: Population of scenario tradespaces

The concepts generated were subsequently modelled and analyzed to populate the tradespaces. NASA's flight optimization system (FLOPS) [15] was employed as the main means of modelling, whereas the cost model developed by [16] was used for the cost analysis, since it allows cost estimation on component level. The cost values were converted to 2016 U.S. Dollars. FLOPS was inadequate to predict the noise for the future engine technologies and it was assumed that the noise levels would be about 20 EPNdB lower than the Chapter 4 standard for the F3STF and only about 10 EPNdB for the open-rotor. To model the open-rotor fuel-flow, an engine-deck for a generic open-rotor, obtained from PACELAB [17], was used. Models were created to estimate the LTO NOx emissions based on the LTO fuel flow and scaled notional values for LTO NOx values presented in [10] and [18]. The area of laminar flow (LF) on the wing was predicted using a model from [19]. Fuel flow for the F3STF and CROR was estimated by scaling values presented in [10] and [18], respectively. Fractions of fuselage mass was added to the concepts employing the open-rotor, based on expected increases discussed in [18]. [20] was used for the BFL estimates. After modelling was complete, a full-factorial DoE was performed with the parameters shown in Table 2 to populate the tradespaces. The resulting tradespaces can be seen in Fig. 5.

Table 2: Design-of-Experiments parameters.

	Conventional		T-tail	
Parameter/ component	**EIS 2020**	**EIS 2030**	**EIS 2020**	**EIS 2030**
Engine type	2015 TF	F3STF	2015 TF	F3STF, CROR
Flap type	SSF, TSF	SSF, TSF	SSF, TSF	SSF, TSF
Slat	Yes	Only non-LF	Yes	Only non-LF
LF (N=None, P=Passive)	N	N; P	N	N; P
Thrust [lbf]	Min=20 000; Max=30 000; 6 Levels			
Span [ft]	Min=105; Max=130; 6 Levels			
Root chord [ft]	Min=17; Max=23; 7 Levels			
Cruise Mach number	0.78	0.78; 0.73(LF)	0.78	0.78; 0.73 (LF)
Quarter-chord sweep [°]	25°	25°, 4°(LF)	25°	25°, 4° (LF)

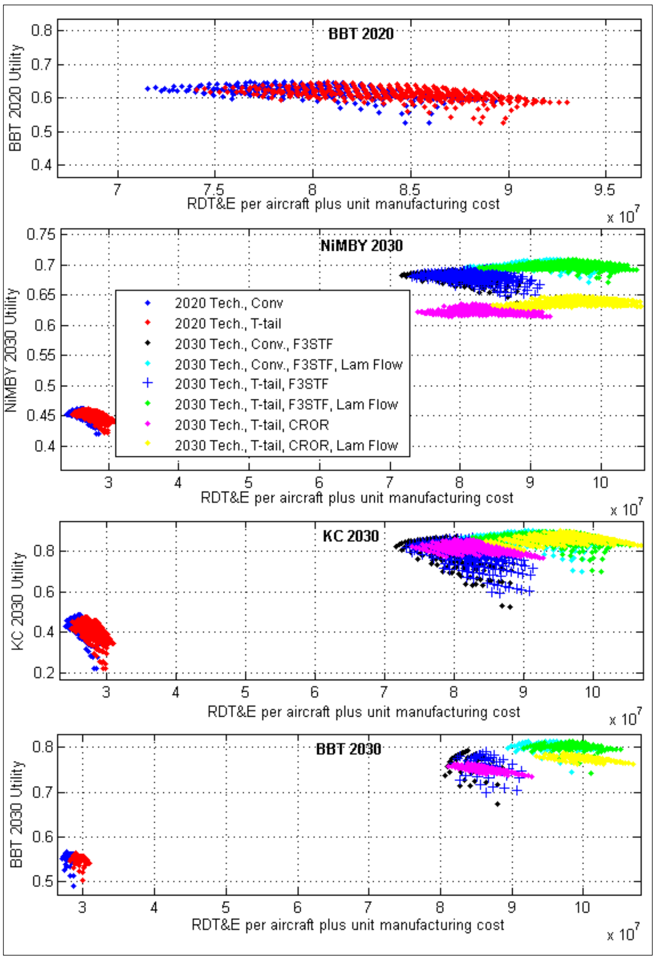

Fig. 5: Tradespaces for the scenarios. The legend applies to all the plots.

Step 4: Identification of potential transition paths

After the tradespaces were populated, the region of interest could be selected for each scenario. Fig. 6 shows the region of interest for the T-tail in KC 2030. As can be seen, affordability is important in this scenario, but reasonable performance is still expected. Once the regions of interest for both the configurations in all the scenarios had been identified, the designs falling in these regions were compared to find potential transition paths. Fig. 7 shows a parallel coordinates plot of the T-tail designs of interest for the different scenarios. As can be seen, large values of span and root chord are favored in BBT 2030, whereas the opposite is true for KC 2030 and BBT 2020. Also, the only scenario in which the open-rotor is a desirable option is in KC 2030. The designer can now use this plot to find what parameters can be made common.

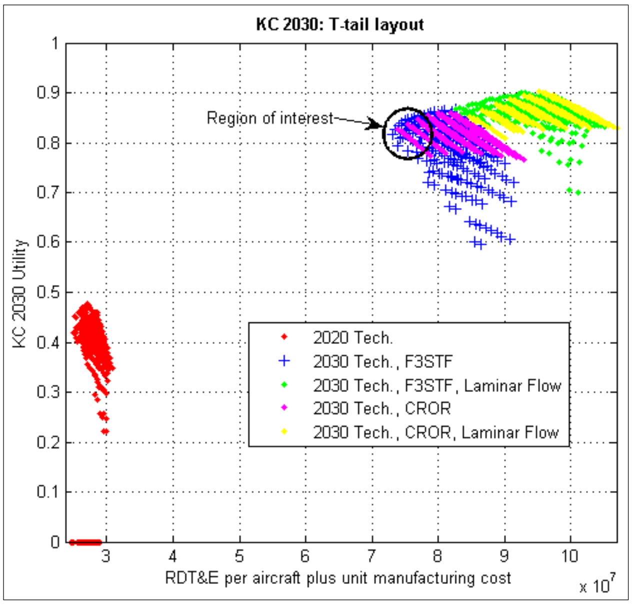

Fig. 6: Region of interest for T-tail in KC 2030.

One possible solution (for the T-tail configuration) is shown in Fig. 8. As can be seen, transition paths are required to enable a span increase from 110ft to 125ft, as well as a root chord increase from 18ft to 19ft for BBT 2020 to BBT 2030. There was no change required in these parameters for BBT 2020 to NiMBY 2030 and KC 2030. However, there was a change required from a non-laminar wing to a laminar wing for BBT 2020 to NiMBY 2030.

Also, although span and root chord is the same from BBT 2020 to NiMBY 2030, the wing mass would likely differ between these two scenarios. In other words, although the wing geometry may be the same, a transition path could still be formulated to change to a wing with a different mass. Finally, provision needed to be made for the engine changes as well.

Note that Fig. 8 shows that, for this example, the parameters sets have been reduced to only one combination per scenario. This need not be the case and, indeed, sets should always be considered. The options for the transition paths for the t-tail are now as follows:

- Retain airframe design, develop new systems and re-engine (only possible for BBT 2020 to KC 2030)
- Re-engine, develop completely new wing, new undercarriage, new systems, and retain fuselage and empennage where possible.
- Re-engine, develop a partially new wing (retain root section) and new systems, retain undercarriage, and retain fuselage and empennage.

The designer could just as well have wished to rather select designs that all have common wing geometry and only look at re-engining options. To do this, he/she may ‘drag’ the points of the parallel coordinates plot that relate to span and root chord to specify the geometry that is desired. As stated earlier, this could result in designs with decreased performance.

However, for the purposes of this discussion, it is assumed that the designer is happy with the transition paths selected.

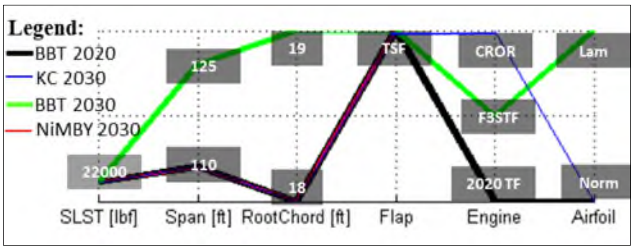

Fig. 8: Selected parameter ranges for T-tail designs.

Step 5: Modelling and simulation of transition paths

Next, the transition paths identified in the previous step were modelled and analyzed. For the re-engine rule, it was only necessary to ensure that the airframe and undercarriage will have sufficient structural strength for incorporating the new engine. This was done by determining whether any of airframe components of the aircraft with the future engines are heavier than

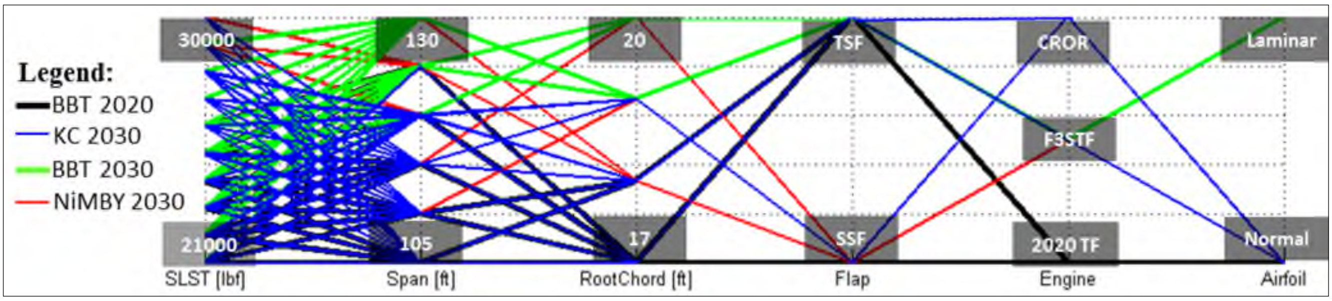

Fig. 7: Parallel coordinates plot showing the T-tail designs of interest for the different scenarios.

that of the aircraft with the older engine. The only future engine for which this will be the case was the CROR, which would require structural treatments to its fuselage to deal with fatigue and noise. These treatments will, however, be added when the new aircraft is developed. For the re-engine and complete new wing, the fuselage and empennage were kept common to the 2020 airframe (their mass values fixed as inputs to FLOPS) and a new wing and undercarriage were designed. For the partial re-wing, the inner root section of the wing, up till just past where the main undercarriage is attached to the wing, was kept common (Fig. 9), whereas the outer wing was re-designed. To be able to do this, it was required to know the mass distribution with respect to span of the wing and, for this purpose, a method to determine wing mass distribution, presented in [21], was employed.

For the BBT 2030 wing, the common section of the wing will also require a 1ft chord increase (visible in Fig. 9). The negative effects of having a common wing section is more mass and (in the case of laminar wings) there is reduced laminar flow area, which meant smaller reductions in fuel-burn attainable than with a full laminar wing.

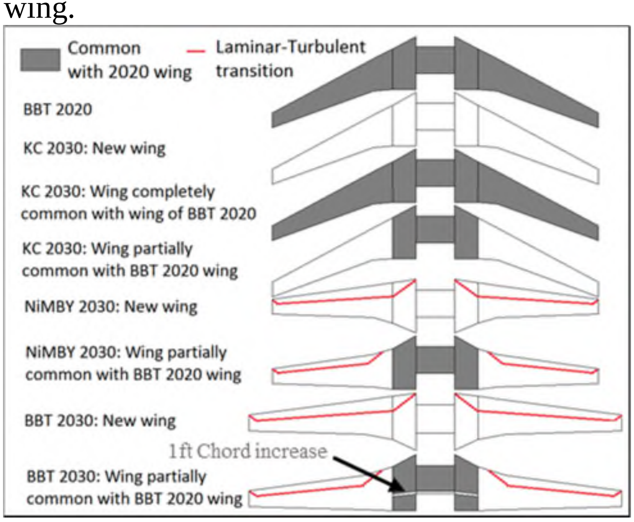

Fig. 9: Wings for the different scenarios. Sections common to the 2020 wing is shown in grey.

Step 6: Final down-selection

When the cost and utilities of all the designs, including those with planned changeability, had been determined, the final down-selection of candidates took place. For this purpose, the metrics in [4] could have been be used. However, because the number of designs, scenarios, and generations was small, visual inspection of the MATs sufficed. For example, Fig. 10 shows the MATs for the first-generation designs (BBT 2020), and one of the three scenarios (BBT 2030) for the second-generation. As can be seen, the changeable designs (A and B) maintain high utility at much reduced cost in the second generation, as compared with completely new designs. This utility is slightly smaller than what can be achieved with new designs, however.

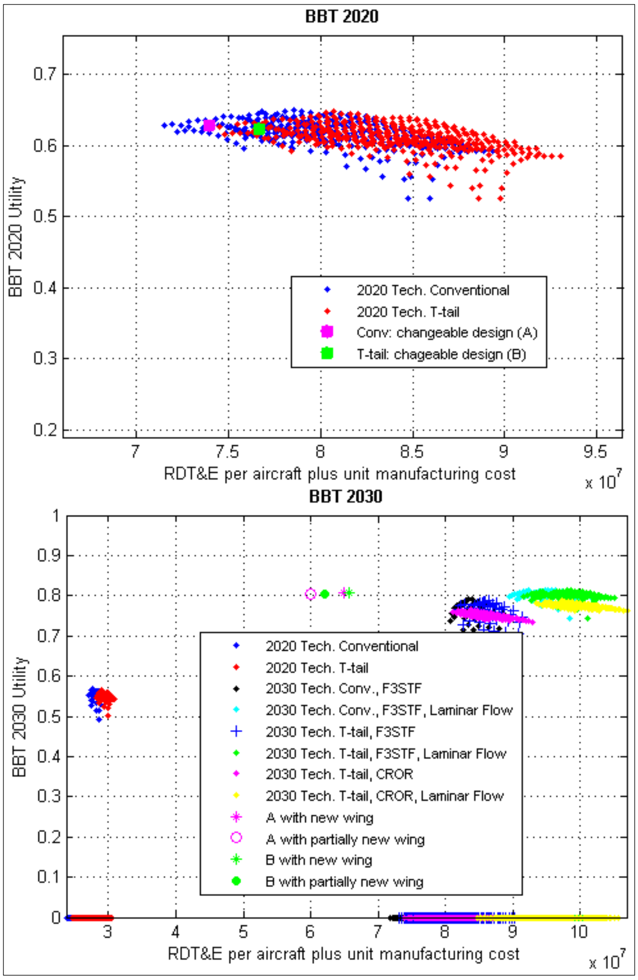

Fig. 10: MATEs for BBT2020 and one of the future scenarios (BBT2030) showing designs with planned (in BBT2020) and executed changeability (in BBT 2030).

6 Conclusions and future work

In this paper, a framework was proposed that employs concepts from Multi-Attribute Tradespace Exploration and Epoch-Era Analysis, along with interactive commonality identification, to enhance the exploration of aircraft changeability during conceptual design. In particular, it was demonstrated how a designer could compare the changeability of aircraft with different top-level configurations and to interactively identify where transition paths need to be inserted. A strong focus in this paper was to search for commonality to identify transition paths. However, it is important to note that enabling changeability is not simply about enforcing commonality, and other architectural aspects (changeability principles), such as simplicity and independence need to be considered as well. Some of these are implicitly incorporated in the proposed framework, as different top-level configurations and systems architectures are investigated together. However, more work is required to further investigate the implications of the other changeability principles within the context of the framework.

The next step would be to implement the framework into a software called 'AirCADia Explorer' [22]. This software employs object-oriented techniques to enable the synchronization of different plots of the design and performance spaces, which will allow the interactivity of the framework to be exploited. Future work will also concern the further development of the methods to enable more scenarios and architectures to be explored. Also, it is endeavored to investigate how object-oriented techniques can be employed to automate selected steps of the framework. Finally, it is aimed to evaluate the framework within an industrial setting.

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