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A Set-Based Approach to Passenger Aircraft Family Design

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Presented is a novel method for the design of passenger aircraft families at early stages of product development. Existing methods employ sequential, optimization-based approaches in which a single design solution is selected early in the design process and is then iteratively modified until all requirements are satisfied. The challenge with such approaches is the tendency of the optimizers to exploit assumptions already 'hard-wired' in the computational models. Subsequently the design is driven towards a solution which, while promising to the optimizer, may be infeasible due to the factors not considered by the models, e.g., promising novel technological solutions. The proposed method for aircraft family design generates multiple solutions from the start by integrating initial design variables sets (ranges) and systems architectures sets. These candidate solutions are then carried forward into the conceptual design stage. The feasible solutions set is determined next and is further narrowed-down by tightening the known constraints and/or by introducing further constraints related, for example, to manufacturing and maintenance. Computational enablers are identified for each stage of the proposed design process. The proposed method has been evaluated through a notional example of a three-member aircraft family design. The evaluation case was presented to a panel of industrial experts who were asked to give feedback on the merits and potential challenges of the approach. The conclusion is that the proposed method is expected to enable the designers to better utilize their knowledge and to provide an environment where they can foster innovation by bringing more design knowledge early into the conceptual design stage. It was pointed out, however, that while the enablers are reaching a stage of sufficient maturity, allowing a multitude of design concepts including systems architectures to be analyzed rapidly and simultaneously, this still is

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expected to present a challenge from a computational and organizational resource point of view.

Nomenclature

n_{fv}	=	number of aircraft family variants
C_i	=	ith performance constraint
n_c	=	number of performance constraints
V_i	=	ith design variable set
D_i	=	domain of V_i
n_v	=	number of design variables
V_i^+	=	ith aggregated design variable set
V_i^{d+}	=	ith discretized aggregated design variable set
p_i	=	number of elements in V_i^{d+}
n_{mc}	=	number of major components in aircraft
MC_j	=	jth major component set
q_j	=	number of elements in jth major component set
SA	=	systems architectures set
n_{sa}	=	number of elements in SA
f_i	=	ith function
n_f	=	number of decomposed functions
$(x_j)_{f_i}$	=	jth solution for the ith function
r_i	=	number of solutions for the ith function
A	=	aircraft set
n_a	=	number of elements in aircraft set
n_{cv}	=	number of common variables among variants
n_{ev}	=	number of exclusive variables among variants
A_S	=	aircraft set for short aircraft family variant

A_B = aircraft set for baseline aircraft family variant

A_L = aircraft set for long aircraft family variant

AF = aircraft family set

n_{af} = number of elements in aircraft family set

I. Introduction

The key to success in today's highly competitive civil aviation market is to develop aircraft, not only with a superior performance but also with a lower cost of ownership and shorter lead time, while satisfying a wide range of requirements from multiple airlines. In order to achieve this goal, aircraft OEMs develop families. An aircraft family is a group of similar aircraft which employ common major components and systems architectures but satisfy different performance and mission requirements. For example, the latest passenger aircraft family (A350) from Airbus is comprised of three variants (baseline, short, and long) where all the variants have common wing and empennage but each variant has exclusive fuselage in order to accommodate different number of passengers. Besides benefiting aircraft OEMs by reducing costs for tooling, production, and assembly of common components, aircraft families also benefit airlines by reducing maintenance and pilot-training costs. Furthermore, it allows efficient route scheduling.

Aircraft family design entails a significantly different approach compared to a single aircraft design: balancing multiple missions/markets, performances and costs. It involves a trade-off between "commonality among aircraft variants" and "performance of the individual aircraft variants", i.e. increased commonality leads to decreased performance of the individual aircraft variants. In general, product family design can be categorized into two types: module-based and scale-based [1]. In module-based product family design, variants are created by adding, removing, and/or substituting the components in order to achieve different functions, whereas in the scale-based product family design, variants are created by stretching or shrinking the components. Module based aircraft family design is predominantly conceived for military and unmanned air vehicles [2], e.g. attack, bomber, and surveillance aircraft where the components are added/substituted to accomplish variety of different functions. Scale-based aircraft family design is conceived for passenger transport aircraft where major components such as fuselage are scaled. The present research focuses on scale-based passenger aircraft family design. The number of passengers and the range for different Airbus and Boeing aircraft families are shown in Fig. 1. It can be observed that there have been three trends followed when designing passenger aircraft family variants. In the first trend, constant fuel capacity across aircraft family results in a trade-off between number of passengers and range, i.e. as the number of passengers increases, the range decreases (e.g. Airbus A320 family). In the second trend, more fuel capacity and higher-thrust engine (but with the same number of passengers) result in Extended Range (ER) variants. For example, Boeing 777-200 and 777-200ER both have similar fuselage (equal number of passengers), but the later provides longer range. In the third trend, both the number of passengers and the range are increased by introducing higher-thrust engines and more fuel capacity (e.g. Boeing 777-200 and 777-300).

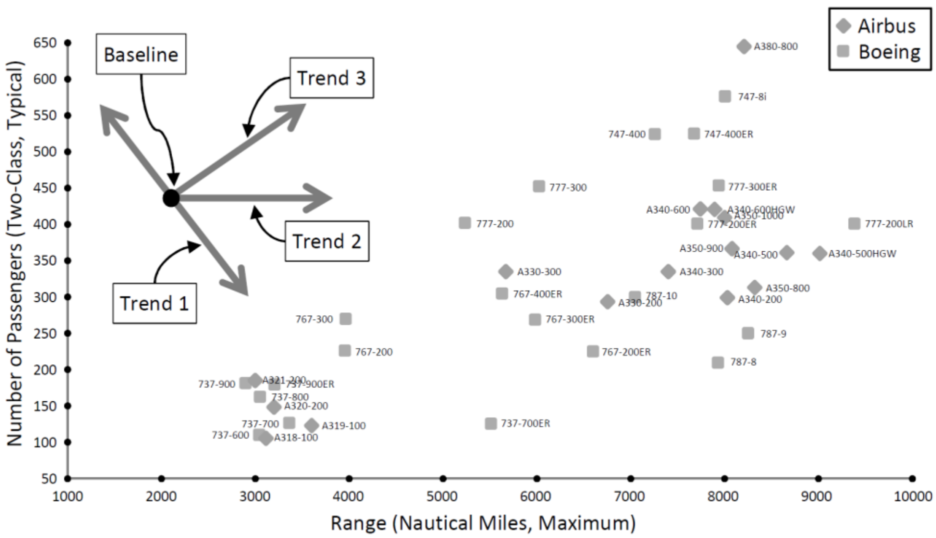

Fig. 1 Passenger aircraft family design trends.

Two scale-based approaches are used in the industry for designing passenger aircraft families: sequential and simultaneous [3]. In the sequential approach, a baseline aircraft is designed first and the variants are designed later, whereas, in the simultaneous approach, baseline aircraft and the variants are designed together. In the past, the sequential approach was used to create passenger aircraft families. For instance, the baseline variant of the Airbus A320 family was first delivered in 1988. This baseline aircraft was later modified to create a long-variant (Airbus A321) in 1994 to satisfy different airlines' requirements.

Subsequently, the family was extended to include the short variants (A319 and A318) in 1996 and 2003, respectively. More recent aircraft programs considered the simultaneous approach, e.g. all the three members of the Airbus A350 family (baseline variant A350-900, short-variant A350-800, and long-variant A350-1000) were launched together in 2006. Researchers have presented methods for sequential development of aircraft families by introducing reserves into the baseline aircraft and using change propagation to develop new variants [4][5][6]. Willcox and Wakayama [3] compared the two approaches in the context of a design study of Blended Wing Body (BWB) aircraft families. The authors claimed that about 1% of the structural weight could be saved when the simultaneous approach is used.

Existing scale-based methods for designing passenger aircraft families employ optimization-based approach. Willcox and Wakayama [3] developed a Multidisciplinary Design Optimization (MDO) framework and demonstrated its use for designing Blended Wing Body (BWB) aircraft family consisting of two variants. Cabral and Paglione [7] developed a multi-objective optimization tool for the conceptual design of passenger aircraft families using Genetic Algorithms (GA). D'Souza and Simpson [8] also demonstrated the use of GA for designing general aviation aircraft family. Allison et al. [9] used decomposition based (multi-level) optimization methods such as the Analytical Target Cascading (ATC) and Collaborative Optimization (CO) for passenger aircraft family design. Later, Roth [10] developed an improved and efficient decomposition-based optimization method, named Enhanced Collaborative Optimization (ECO) which is based on CO, and demonstrated its use for designing passenger aircraft families.

Two problems have been identified with the above mentioned optimization-based approaches. First, if the design requirements change, the optimization-based approaches require restarting the whole process all over again. It is estimated that 35 percent of the delays in product development are due to changes in the product definition/requirements during the design process [11]. The changes in requirements are not only expected from customers but also how other competitors respond to market needs. For instance, Boeing was originally considering to replace the third generation of 737 aircraft family with a clean-sheet design [12]. However, the launch of the second generation of Airbus A320 family (which differs from the first generation primarily in using more efficient engines), forced Boeing to launch a re-engined successor for the third generation of 737 family [13] as customers were not prepared to wait years required for the clean-sheet design. Furthermore, the optimization-based methods have the tendency to exploit assumptions present in the computational models and to drive the design towards a solution which, while promising to the optimizer, may be infeasible due to the factors not considered by the models such as manufacturing, maintenance and novel technologies. The second problem is that the above mentioned methods do not consider systems architectures analysis. Aircraft systems account for roughly one-third of the total aircraft's empty weight [14] and play an important role in aircraft family design where the target is to utilize common systems architecture among all the family variants. Traditionally a top-down approach is used, i.e. the aircraft configurations are frozen before moving on to the systems architectures design where the suppliers are selected and the systems architectures are defined by analyzing systems' layout, interfaces and performance characteristics [15]. The systems architectures are, therefore, optimized in isolation which results in sub-optimal architectures with under- or over-estimated performances due to overlooked interactions between systems and their impact on the whole aircraft. For instance, it was decided to switch the conventional (bleed) Environmental Control System (ECS) to electric (bleed-less) for Boeing 787 in order to lower the aircraft fuel burn and empty weight, but when the aircraft was finally integrated the performance turned out to be same as the conventional ECS [16]. Clearly, switching from a bleed (conventional) to a bleed-less (electric) ECS architecture involves a lot of considerations to take into account while performing initial performance estimation. For example, although engine performance is increased by reducing the bleed air, the ram drag is increased. Similarly, although mass is saved by removing pipes and valves, other heavy components e.g. compressors are added. Therefore, bringing more knowledge earlier into the design process by considering systems architectures analysis and trade-off is expected to enable designers to make better informed decisions.

Within this context, the aim of the presented research has been to develop an interactive methodology for designing passenger aircraft families at the early design stage which:

1. Can better accommodate the changing design requirements.
2. Enables the designers to better utilize their past experience, and gain knowledge about the design space.
3. Provides the designers with an environment to foster innovation by considering systems architectures analysis and trade-off, thus bringing more design knowledge early into the conceptual stage.

The rest of the paper is organized as follows. Section II presents the proposed methodology. Section III demonstrates the application of the proposed approach by using a case-study. Section IV presents critical evaluation by industrial experts and finally the conclusions are drawn in Section V.

II. Proposed Methodology

Existing methods for designing passenger aircraft families employ a sequential "synthesize, analyze, and modify" approach, where the designer(s) select a single concept/architecture fairly early in the design process by utilizing past experience. The selected concept/architecture is then iteratively analyzed and modified until all the goals and requirements are met. This approach is also termed as Point Based Design (PBD) because, at any point in the design process, the designer(s) work with only one design solution. The proposed novel methodology for designing passenger aircraft families embraces the principles of the Set-Based Design (SBD) paradigm [17] [18] in which the design is kept open by the parallel development of multiple design solutions and delaying the critical decisions. As more design knowledge is gained, the set of possible solutions is narrowed-down to converge on a final design by discarding infeasible and inferior solutions. The SBD approach reduces the design rework resulting from the wrong decisions made earlier [19]. Unlike the PBD approach which focuses on selecting the best design, the SBD approach focuses on eliminating the worst designs. The expectation is that the gradual reduction should enable the designer(s) to bring more knowledge early into the conceptual design stage by considering different technical solutions, resulting in better understanding of the design problem through trade-offs. Previous research efforts have presented methods which employ SBD principles [20] [21], but these methods do not consider family design. The authors are not aware of any published methods for product family design which use SBD principles.

A novel methodology (using SBD principles) for the early design of passenger aircraft families is proposed, as shown in Fig. 2. Before explaining the steps of proposed methodology in detail, the key terminologies used in Fig. 2 are defined first. An aircraft is broadly subdivided into three elements: Airframe (structure), Power plant (engines), and systems (equipment) [22]. The term “major component” refers to both airframe and power plant, i.e. structural components of the aircraft such as fuselage, wing, empennage (horizontal and vertical tails), engine(s) and landing gear. The term “system” refers to the group of components (mostly hidden under the floor, inside wings or behind panels) that fulfill essential function. For instance, the system dealing with the function “provide suitable environment for passengers”, i.e. Environmental Control System (ECS), is comprised of components such as ozone converters, air conditioning packs, mixing manifold, air filters, condenser, water extractor, ducts and valves. For each system, the term “system architecture” (aka logical architecture) refers to the abstract description of the constituent components and their interconnections. The term “systems architecture” refers to the ensemble of architectures of all aircraft systems (e.g. Environmental Control System (ECS), Ice Protection System (IPS), Flight Control System (FCS), Electrical Power System (EPS), and so forth). The term “set” refers to the collection of elements from which the designers select a single element as part of the design process. The elements in the set can be both physical objects (such as actuators, wings, aircraft, etc.) and parameters (such as span, reference area, mass, etc.). The proposed aircraft family design methodology is divided into three phases: customer needs mapping, synthesis and analysis, and narrowing-down. The first phase involves the mapping of the customer needs into: 1) performance constraints and 2) initial design variables sets. In the second phase, the design solutions are synthesized at the major components and systems level, which are then combined to generate a set of aircraft. After combination, the set of aircraft is classified into multiple sets of aircraft corresponding to the aircraft family variants, e.g. baseline, short, long etc. Then, the aircraft family set is created by selecting an aircraft from each of the aircraft family variants sets. The third phase involves the gradual reduction of the aircraft family set by discarding the infeasible and inferior aircraft family solutions.

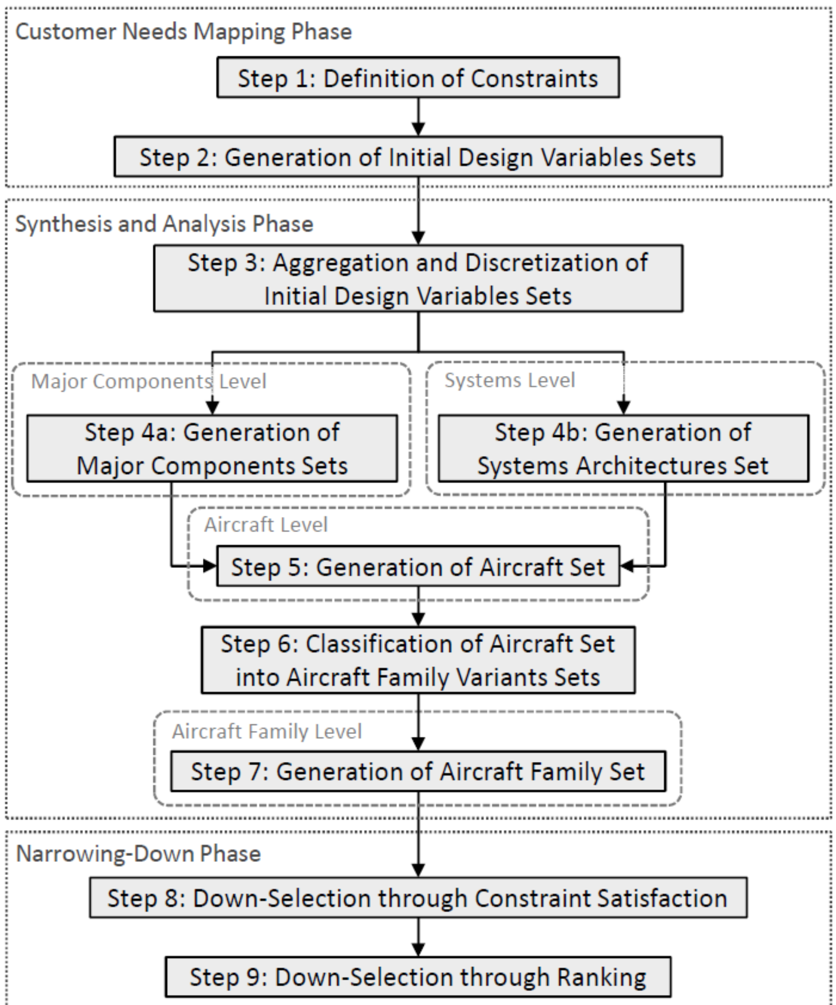

Fig. 2 Proposed methodology for designing passenger aircraft families

The three phases of the proposed methodology, depicted in Fig. 2, are further explained step by step in the following subsections.

A. Phase 1: Customer Needs Mapping

The first phase of the proposed process is concerned with mapping of the customer needs into the constraints and the initial design variables sets of all the aircraft family variants. This phase is comprised of two steps.

Step 1 - Definition of Constraints: In the first step, requirements analysis (as described in engineering standards [23] [24] [25] [26] is used to map the customer needs into constraints which are used during the narrowing-down phase in order to progressively discard the infeasible design solutions. The general form of the constraints C_i is given by Eq. (1) where C_i is the ith constraint, c_i is the limiting value for the ith constraint, and n_c is the total number of constraints.

$$C_i \quad \begin{matrix} = c_i \\ \leq c_i \\ \geq c_i \end{matrix}, \forall\, i = 1, n_c \tag{1}$$

Apart from the customer needs, limiting values of the constraints must also take account of the competitor performance. The output of this step is a collection of constraints $C_i,\ \forall\, i = 1, n_c$ for all the aircraft family variants.

Step 2 - Generation of Initial Design Variables Sets: In this step, the constraints (obtained in Step 1) are used to determine the initial domains of the design variables sets for all the aircraft family variants. Past knowledge/experience is key in determining domains of the design variables sets. In the case of lack of knowledge, the initial domains of the design variables sets are assigned arbitrarily and therefore other exploration means need to be applied for a more precise definition [27].

The general form of the design variable set Vi; 8i = 1; $V_i,\ \forall\, i = 1, n_v$ is given by Eq. (2) where D_i is the domain of the ith design variable, and n_v is the total number of design variables.

$$V_i := D_i, \quad \forall\, i = 1, n_v \tag{2}$$

Many design variables are continuous in nature and their domains are represented by the intervals between a lower and upper bound. However, some design variables are discrete in nature and their domains are represented by the set of options. The general form of the continuous and discrete design variables sets is given by Eq. (3) and Eq. (4), respectively. The lower-case letter v_i represents an element of the design variable set, i.e. $v_i \in D_i$. For the discrete design variable set shown in Eq. (4), v_{i_k} represent the kth element of the set, i.e. $v_{i_k} \in D_i$.

$$V_i := D_i = [LB_i, UB_i] = \{v_i \mid LB_i \leq v_i \leq UB_i \tag{3}$$

$$V_i := D_i = \{v_{i_1}, v_{i_2}, v_{i_3}, \ldots, v_{i_k}\} \tag{4}$$

For example, the set of wing span $V_1 := [30.0, 40.0]m$ and the set of wing material $V_2 := \{aluminium, carbonfibre\}$ are the continuous and discrete design variable sets, respectively. If the domain of a continuous design variable is disjoint, then it can be represented as the union of two or more intervals. Furthermore, if a unique value is part of the continuous design variable domain, then it can be represented by using degenerate interval. The latter is a single valued interval where the lower bound is equal to the upper bound. For example, if the domain of the set of wing span includes a unique discrete value of $39.5m$ and intervals between $31.0m$ to $33.0m$ and $37.0m$ to $39.0m$, then it can be represented by $V_{WingSpan} := [31.0, 33.0]m \cup [37.0, 39.0]m \cup [39.5, 39.5]m$. The outputs from this step are the initial design variables sets $V_i, \ \forall\, i = 1, n_v$ for all the aircraft family variants.

B. Phase 2: Synthesis and Analysis

When designing complex products, such as an aircraft family, multiple (and often geographically distributed) teams are involved. This phase, therefore, involves the synthesis and analysis of partial solutions at major components and systems level by the relevant design teams, which are then combined to create the set of complete aircraft solutions. At the major components level, the sets of major components (e.g. fuselage, wing, empennage, engine(s) and landing gear) are created and the designer chooses which major components should be common or exclusive among aircraft family variants whereas at the systems level, the set of alternative systems architectures is created in order to conduct the trade-off between systems technologies. The set of aircraft is then classified into multiple sets for the corresponding aircraft family variants. Finally, the set of aircraft family is created by selecting an aircraft from each of the aircraft family variants sets. The synthesis and analysis phase is comprised of six steps.

Step 3 - Aggregation and Discretization of Initial Design Variables Sets: The first step at the synthesis and analysis phase is to aggregate all the initial design variables sets $V_i, \ \forall\, i = 1, n_v$ (obtained in Step 2) of the aircraft family variants. The aggregation process enables to employ a sampling strategy to generate a sufficiently large population of aircraft that is a representative of all the aircraft family variants. The ith aggregated design variable set is represented by ${V_i}^+, \ \forall\, i = 1, n_v$. Mathematically, the ith aggregated design variable set ${V_i}^+$ is the union of the ith domains of initial design variables set of the individual aircraft family variants, which is given by Eq. (5) where n_{fv} is the number of aircraft family variants and D_i is the domain of the ith design variable set.

$$V_i^+ := D_i^+ = (D_i)_1 \cup (D_i)_2 \cup \ldots \cup (D_i)_{n_{fv}}, \quad \forall\, i = 1, n_v \qquad (5)$$

For an aircraft family of three variants, $n_{fv} = 3$ (e.g. Baseline, Short, and Long), the ith aggregated design variables set is given by Eq. (6) where the symbols S, B, and L represent short, baseline, and long variants, respectively.

$$V_i^+ := D_i^+ = (D_i)_S \cup (D_i)_B \cup (D_i)_L, \quad \forall\, i = 1, n_v \tag{6}$$

For example, if the initial design variables sets for the wing span of the short, baseline, and long variants are $[25.0, 35.0]m$, $[30.0, 40.0]m$, and $[35.0, 45.0]m$, respectively, then the aggregated wing span set is given by $V^+{}_{WingSpan} := [25.0, 35.0]m \cup [30.0, 40.0]m \cup [35.0, 45.0]m = [25.0, 45.0]m$.

After aggregation, continuous aggregated design variables sets ${V_i}^+$ are discretized in order to achieve a finite number of elements. The discretized aggregated design variables sets are represented by ${V_i}^{d+}$, $\forall\, i = 1, n_v$. The cardinality (number of elements) of the ith discretised aggregated design variables sets ${V_i}^{d+}$ is represented by p_i, i.e. $p_i = |{V_i}^{d+}|$ where two vertical bars represent the cardinality of the set. The sampling strategy should be selected such that the sampled points are adequately distributed throughout the extent of the aggregated design variables sets ${V_i}^+$.

Step 4a - Generation of Major Components Sets: In this step, the discretized aggregated design variables sets ${V_i}^{d+}$ obtained in Step 3 are used to create the sets of major components. The jth major component set is represented by MC_j, $\forall\, j = 1, n_{mc}$ where n_{mc} is the number of major components. Mathematically, the set of the jth major component MC_j is the Cartesian product of the discretized aggregated design variables sets ${V_i}^{d+}$belonging to the jth major component, which is given by Eq. (7).

$$MC_j := V_1^{d+} \times V_2^{d+} \times \ldots \times V_i^{d+} \times \ldots \times V_{n_v}^{d+}, \quad \forall\, j = 1, n_{mc} \mid i = 1, n_v \wedge V_i \in MC_j \tag{7}$$

Given n discretised sets $A_1, A_2, \ldots, A_n$, the Cartesian product (written as $A_1 \times A_2 \times \ldots \times A_n$) is the set of all the ordered n-tuple ($a_1, a_2, \ldots, a_n$) where $a_i \in A_i$, $\forall\, i = 1, n$. Therefore, the cardinality of the jth major component set, represented by q_i, is given by Eq. (8).

$$q_j = |MC_j| = \prod_{i=1}^{n_v} p_i, \quad \forall\, j = 1, n_{mc} \mid V_i \in MC_j \tag{8}$$

For instance, the two discretized aggregated design variables sets for wing span and area ${V_1}^{d+} := \{30, 40\}m$ and ${V_2}^{d+} := \{110, 120, 130\}m^2$, respectively (with $p_1 = 2$ and $p_2 = 3$) will result in the creation of a set of wings with $q_{wing} = p_1 \times p_2 = 2 \times 3 = 6$, i.e. $MC_{wing} := \{w_1, w_2, w_3, w_4, w_5, w_6\} = \{(30, 110), (30, 120), (30, 130), (40, 110), (40, 120), (40, 130)\}$, where $w_1 = (30, 110)$ (wing with span and area equal to $30m$ and $110m^2$, respectively), $w_2 = (30, 120)$, $w_3 = (30, 130)$ and so forth. Apart from synthesis, this step also involves analysis to evaluate the wing performance parameters, e.g. weight, cost, lift-to-drag ratio, etc. Later during the integration of major components and systems architecture (i.e. Step 5), these parameters will be used to evaluate performance parameters at the aircraft level, e.g. take-off field length, approach speed, block fuel, etc. Similar to the set of wings, the sets of other major components (e.g. fuselage, engines, horizontal and vertical tails etc.) are synthesized and analyzed in this step by relevant teams.

Step 4b - Generation of Systems Architectures Set: This step involves synthesis and analysis of a set of systems architectures. The set of systems architectures SA is represented by Eq. (9) where n_{sa} is the cardinality of the systems architecture set, i.e.$n_{sa} = |SA|$, and the lower case letter sa represents a systems architecture.

$$SA = \{sa_1, sa_2, sa_3, \dots, sa_{n_{sa}}\} \tag{9}$$

The set of systems architectures SA can be generated by utilizing functional analysis, as described in systems engineering standards [23] [24] [25] [26]. Functional analysis is the process of identifying toplevel functions (which are the functional requirements identified in the requirements analysis), and decomposing into lower-level functions. The performance requirements are then allocated to these lower-level functions. The set of all the lower-level (leaf) functions for aircraft systems F is represented by Eq. (10) where n_f is the cardinality of the set of decomposed functions for aircraft systems.

$$F = \{f_1, f_2, f_3, \dots, f_{n_f}\} \tag{10}$$

Once the set of lower-level functions for aircraft systems F is identified, various solutions (of varying technological maturity) may be devised to realize these functions which results in different systems architectures. A solution may be either a single component or a group of components connected together to perform a particular function. Giving focus to the functions that the product must perform, rather than on the physical solutions, helps the designers to foster innovative systems architectures [23]. In other words, it prevents the designers from immediately elaborating on the first physical solution that comes into mind, which may not be the best. The set of physical solutions for the ith function X_i is represented by Eq. (11) where $(x_j)_{f_i}$ is the jth solution to realise the ith function, and r_i is the cardinality of the set of physical solutions for the ith function X_i, i.e. $r_i = |X_i|$.

$$X_i = \{(x_1)_{f_i}, (x_2)_{f_i}, \dots, (x_j)_{f_i}, \dots, (x_{r_i})_{f_i}\}, \quad \forall\, i = 1, n_f \tag{11}$$

The total number of systems architectures n_{sa} that can be generated by combining different solutions of all functions is given by Eq. (12). It should be noted that the development of systems architectures is a creative, iterative and recursive process that requires a good knowledge of different potential solutions to realize systems functions.

$$n_{sa} = |SA| = \prod_{i=1}^{n_f} r_i \tag{12}$$

After synthesis, these architectures are analyzed using mathematical models in order to conduct trade-off during the 'narrowing-down phase' where a common (best) systems architecture is selected that satisfies the requirements of all the aircraft family variants. In order to evaluate the systems architectures, the performance characteristics (such as weight, cost and power off-take) of the whole systems architecture are obtained by aggregating the performance characteristics of the individual physical solutions.

Step 5 - Generation of Aircraft Set: After generating the sets of major components MC_j (obtained in Step 4a) and the set of systems architectures SA (obtained in Step 4b), the design solutions at major components and systems level are combined to create a set of aircraft, represented by A. It should be noted that although the steps 4a "Generation of Major Components Sets" and 4b "Generation of Systems Architecture Set" are explained in sequence, both steps are executed in parallel (see Fig. 2). Furthermore, the two steps are not executed independently, in fact the synthesis and analysis activities at both (major components and systems) levels require communication in between through data inputs/outputs. Mathematically, the set of aircraft A is the Cartesian product of the sets of major components MC_j and the set of systems architecture SA, which is given by Eq. (13). The cardinality of the set of aircraft A is represented by n_a, which is given by Eq. (14).

$$A = MC_1 \times MC_2 \times \dots \times MC_j \times \dots \times MC_{n_{mc}} \times SA \tag{13}$$

$$n_a = |A| = n_{sa} \prod_{j=1}^{n_{mc}} q_j = \prod_{i=1}^{n_f} r_i \prod_{j=1}^{n_{mc}} q_j \tag{14}$$

For example, the set of aircraft A for six major components sets (fuselage MC_F , wing MC_W, horizontal tail MC_{HT}, vertical tail MC_{VT} , engine MC_E, and landing gear MC_{LG}) and systems architectures set SA is given by Eq. (15).

$$A = MC_F \times MC_W \times MC_{HT} \times MC_{VT} \times MC_E \times MC_{LG} \times SA \quad (15)$$

After synthesizing the set of aircraft A, the analysis deals with the evaluation of the aircraft level performance parameters (e.g. block fuel, flyover/sideline take-off noise, nitrogen oxide emissions, take-off field length, etc.) using computational models.

Step 6 - Classification of Aircraft Set into Aircraft Family Variants Sets: This step is concerned with the classification of the set of aircraft A (obtained in Step 5) into multiple sets $A_k, \ \forall\ k = 1,\ n_{fv}$ corresponding to the desired aircraft family variants where n_{fv} is the number of aircraft family variants. The aircraft sets for all the family variant $A_k, \ \forall\ k = 1,\ n_{fv}$ are the subset of the set of aircraft A, i.e. $A_k \subset A$. In this step, exclusive variables are classified into multiple sets corresponding to the aircraft family variants. For the two variables, number of passengers $Npax$ and aircraft range R, the set of the aircraft for the kth family variant A_k is given by Eq. (16) where a represents an aircraft belonging to the set of aircraft A, $Npax_a$ and R_a represent the number of passengers and range of aircraft a, respectively. The minimum and maximum values of the number of passengers for the kth aircraft family variant is represented by $min(Npax_k)$ and $max(Npax_k)$, respectively. Similarly, $min(R_k)$ and $max(R_k)$ represent the minimum and maximum values for the range of the kth family variant. The minimum and maximum values for the classification parameters are decided by the designer(s) based on customer requirements and market surveys. For example, if the minimum and maximum values for the number of passengers and range of the baseline variant are chosen as $[160, 180]$ and $[2950, 3050]nm$, respectively. Then the set of baseline aircraft variant A_B includes all the aircraft of the set A which have number of passenger and range capacity in between $[150, 160]$ and $[2500, 3000]nm$, respectively.

$$A_k = \{a \mid a \in A \wedge \min(Npax_a) \leq Npax_a \leq \max(Npax_a) \wedge \min(R_a) \leq R_a \leq \max(R_a)\} \quad (16)$$

For example, considering three aircraft family variants (short, baseline, and long), the set of fuselage MC_F will be subdivided into three sets of fuselage $(MC_F)_S$, $(MC_F)_B$, and $(MC_F)_L$. The cardinality of the subdivided sets of fuselage is represented by $(q_F)_k,\ \forall\ k, k = 1, n_{fv}$.

Step 7 - Generation of Aircraft Family Set: The set of aircraft family AF is created by the Cartesian product of the sets of aircraft family variants $(A_v)_i$ such that common major components are same for all the family variants. Each element of the set of aircraft family AF is a combination of three aircraft variants with common major components and systems.

$$AF = \left\{(A_v)_1 \times (A_v)_2 \times \ldots \times (A_v)_{n_{fv}}\right\} \tag{17}$$

Those combinations which will result in different common major components will not be selected. The number of aircraft families n_{af} created in AF is given by:

$$n_{af} = n_{sa} \cdot \prod_{i=1}^{n_{cv}} p_i \cdot \prod_{i=1}^{n_{ev}} \prod_{k=1}^{n_{fv}} p_{i_k} \tag{18}$$

Here, n_{cv} is the number of common design variables sets, n_{ev} is the number of exclusive design variables sets, and n_{fv} is the number of aircraft family variants. Furthermore, p_{i_k} represents the ith design variable for the kth aircraft family variant.

In this step, the designer chooses which major components will be common among the aircraft family variants. Typical common major components would be wing, empennage (horizontal tail + vertical tail), whereas fuselage, landing gear, and engines could be exclusive to the individual family variants. The exclusive fuselages among the family members allow to satisfy varying airlines' requirement for the different number of passengers. The reason for exclusive engines is to provide optimum sea-level static thrust for individual family members, since oversized engines consume more fuel while undersized engines result in longer take-off field length. The weight of the landing gear is usually about the $1/10th$ of the whole aircraft weight [14]. Therefore, exclusive landing gears are normally used among aircraft family variants. Again, the choice of common or exclusive component depends on the designers' preference. For example, the Airbus A350 family shares a common landing gear between -900 and -800, whereas the Boeing 787 family employs exclusive landing gears for 787-8 and 787-9 variants.

After synthesizing the set of aircraft family AF, the aircraft families are analyzed for evaluating updated performances and the family cost. It was mentioned earlier that a common systems architecture is used for all the variants when designing passenger aircraft families. The systems' components are, therefore, sized to meet the maximum requirements. For instance, if the maximum electrical power required by the systems of short, baseline, and long variants are $300kW$, $330kW$, and $360kW$, respectively, then the electrical generators are sized for $360kW$ (maximum required value) so that the same electrical generator can satisfy the requirements of all aircraft family variants. This means that smaller aircraft variants tend to have more over-sized systems' components. Therefore, after generating the set of aircraft family AF, the analysis at this step involves estimating updated performance parameters for each of the variants. Furthermore, the cost of the whole family needs to be calculated by taking care of the common components. When components are shared among multiple aircraft, the Research, Development, Testing and Evaluation (RDTE) cost is also shared among all the family members, although a small additional cost is associated with developing components for use on multiple aircraft.

C. Phase 3: Narrowing-Down

In the down-selection phase, infeasible and inferior design solutions from the set of aircraft family are progressively discarded. This phase is comprised of two steps.

Step 8 - Down-Selection through Constraint Satisfaction: In the first step of the 'narrowing-down phase', the solutions from the aircraft family set are assessed against the constraints of the individual aircraft family variants. First, the constraints obtained in Phase 1 are applied on the sets of aircraft family variants A_i, and then the feasible sets of the aircraft family variants are intersected in order to determine the reduced sets of common design variables. It is important to note that, unlike traditional optimization-based approaches which consider fixed constraints, the proposed methodology considers the ranges of constraints by enabling the designers to change the constraints' limiting values in real-time, in order to account for changing customer requirements.

Step 9 - Down-Selection through Ranking: After reducing the set of aircraft family to a feasible subset by applying the constraints, the next step is to further narrow-down the feasible aircraft family set by ranking. This step involves determining the best aircraft family designs from the set of feasible aircraft families. It was mentioned earlier that aircraft family design involves a trade-off between the 'commonality among aircraft variants' and the 'performance of the individual aircraft variants'. Therefore, non-dominated sorting [28] can be used to filter out the best aircraft family solutions, based on two parameter e.g. economic efficiency and performance efficiency. Among a set of aircraft family AF, the non-dominated set of aircraft family solutions are those that are not dominated by any other member of the set AF.

A design solution $x1$ is said to dominate the other solution $x2$, if both conditions 1 and 2 are true:

1. The solution $x1$ is no worse than $x2$ in all objectives.

2. The solution $x1$ is strictly better than $x2$ in at least one objective.

III. Demonstration

In this section the proposed methodology is demonstrated through an application case-study. The objective is to highlight the capabilities and potential benefits, rather than to come up with the 'best' aircraft family. Publicly available computational models (sizing codes) are used for performance evaluation, therefore the data and numbers shown in this case-study are realistic, but may not be real. An aircraft sizing code from NASA named FLOPS [29] is used for the analysis of major components and aircraft level performance evaluation, while several published methods [30] [31] are used for the analysis of systems architectures. Furthermore, an in-house built software tool AirCADia [32] is used to integrate and execute the codes. It is important to emphasize that the tools/enablers used in this section are not exclusive. Practicing designers may use tools of their own choice for each step of the proposed methodology.

The section is divided into two parts. First, the application case-study is described briefly, and then the individual steps of the proposed methodology are applied on the case-study.

A. Application Case-Study

The aircraft family to be designed is considered to include three members: baseline, short and long variants. All the members are considered to have the same fuel capacity (i.e. fulfilling 'Trend 1' in Fig. 1 where number of passenger is traded against aircraft range and vice versa). The nomenclature is listed in Table 1.

Table 1 Nomenclature for application case-study

Symbol	Name	Unit
N_Pax	Number of Passengers	-
N_Pax_E	Number of Passengers (Economy)	-
Rng	Aircraft Range	$[nm]$
MTOW	Maximum Take-Off Weight	$[lb]$
TWR	Thrust-Weight Ratio	-
FASM	Fuel per Available Seat Mile	$[lb/nm]$
TOFL	Take-Off Field Length	$[ft]$
Vapp	Approach Velocity	$[kt]$
FONoise	Flyover Noise	$[dB]$
SLNoise	Sideline Noise	$[dB]$
NOx	Nitrogen Oxide Emissions	$[lb]$
FuelCap	Fuel Capacity	$[lb]$
Fuel	Block Fuel	$[lb]$
L_F	Fuselage Length	$[ft]$
S_W	Wing Reference Area	$[ft^2]$

AR_W	Wing Aspect Ratio	-
TCR_W	Wing Thickness-Chord Ratio	-
Phi_W	Wing Quarter-Chord Sweep	$[deg]$
S_HT	Horizontal Tail Reference Area	$[ft^2]$
AR_HT	Horizontal Tail Aspect Ratio	-
TR_HT	Horizontal Tail Taper Ratio	-
Phi_HT	Horizontal Tail Quarter-Chord Sweep	$[deg]$
S_VT	Vertical Tail Reference Area	$[ft^2]$
AR_VT	Vertical Tail Aspect Ratio	-
TR_VT	Vertical Tail Taper Ratio	-
Phi_VT	Vertical Tail Quarter-Chord Sweep	$[deg]$
SLST	Engine Sea-Level Static Thrust	$[lb]$
BPR	Engine Bypass Ratio	-
L_MLG	Main Landing Gear Length	$[in]$

Configuration: The single-aisle tube-and-wing configuration (low-wing, two wing-mounted turbofan engines, and conventional tail), which is expected to be the choice for future passenger aircraft families until at least 2030 [33], is considered. All members of the aircraft family are assumed to have common wing and empennage (horizontal and vertical tail), but the fuselages, engines and landing gears are considered exclusive. Although the fuselage length, engine sea-level static thrust, and landing gear mass will be different for the three variants, the fuselage cross-section, engine dimensions/weight, and landing gear length will be the same, which is in line with the industrial practices for passenger aircraft family design.

Systems Architectures: Unlike traditional methods for designing passenger aircraft families, which quickly select a single systems architecture and then focus on optimizing the architecture, the proposed methodology considers a set of systems architectures.

In conventional systems architectures, four types of secondary power (pneumatic, mechanical, hydraulic, and electrical) are used [34], as depicted in Fig. 3. Pneumatic power is mainly used by Environmental Control System (ECS) and Ice Protection System (IPS). Pneumatic power is highly inefficient for ECS since the bleed air extracted from the engine is over compressed and overheated, i.e. it exceeds the safe levels for delivery to downstream components such as Air Conditioning Pack (ACP). Therefore, a ram air heat exchanger (pre-cooler) is used to achieve the desired low temperature of the bleed air, discharging excess energy back into the atmosphere as waste heat that can reach up to 30% [16]. Furthermore, it is very difficult to detect bleed air leaks, and the negative effect of bleed air extraction on high bypass ratio engine's efficiency is more severe [15]. Hydraulic power is mainly used by Flight Control System (FCS), thrust reverser actuation and landing gear. Although hydraulic power is very efficient (high power density), heavy components of centralized hydraulic power system (reservoirs, pumps, pipes, etc.), and potential leakage of corrosive and flammable hydraulic fluid are the major drawbacks of hydraulic power.

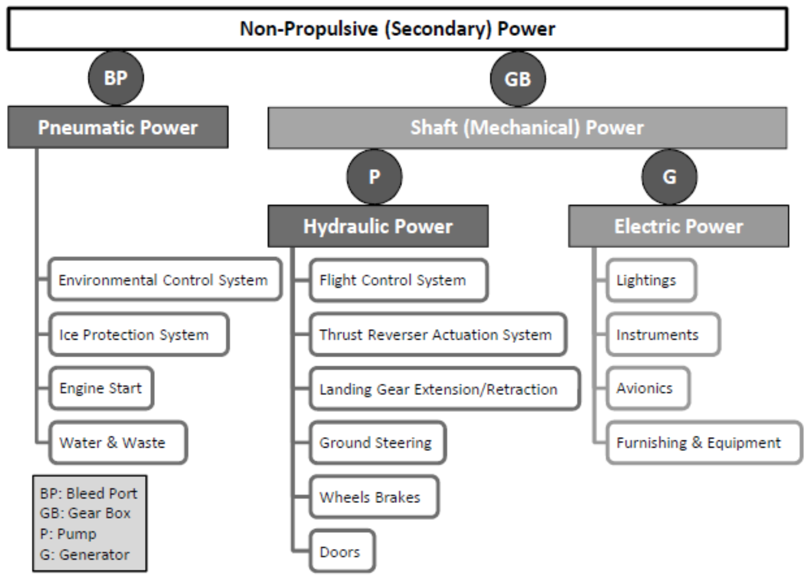

Fig. 3 Types of secondary power used in conventional systems architecture.

Due to the problems mentioned above, there has been a major trend change in the design of aircraft systems. In the last decade or so, the trend has been towards 'All-Electric (AE)' systems architectures where the use of electrical technologies is increasing for systems which have traditionally been powered by pneumatic or hydraulic systems. In an AE systems architecture, all systems use electrical power for operation, as depicted in Fig. 4.

Passenger aircraft family manufacturers seek evolution (rather than revolution) due to the enormous risks involved; therefore currently there is no passenger aircraft family available in the market with AE systems architecture despite the expected benefits. Instead the transition is progressive, leading to 'More-Electric (ME)' systems architectures. For instance, Boeing utilized electrical technologies for 787 ECS and wing IPS, eliminating the Pneumatic Power Systems (PPS) [35]. On the other hand, Airbus utilized Electro Hydrostatic Actuators (EHA) (in parallel with hydraulic actuators) for A380 FCS, reducing hydraulic power use [36]. Therefore, multiple systems architectures (conventional, AE, and ME) are considered, which enables to conduct trade-off between performance/ efficiency and risks.

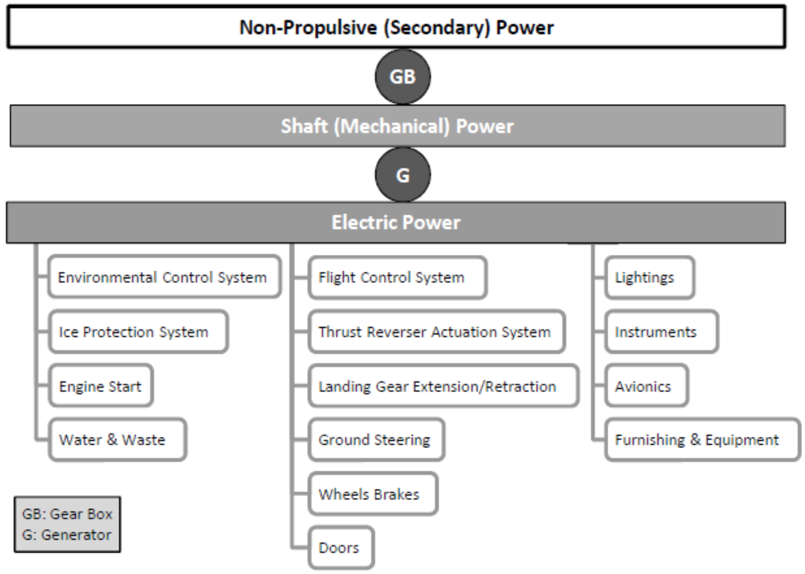

Fig. 4 Types of secondary power used in all-electric systems architecture.

B. Implementation

In this subsection, individual steps of the proposed methodology are applied on the application case-study using relevant enablers.

Step 1 - Definition of Constraints: In this step, the House of Quality (HoQ) [37] is employed for the definition of performance constraints for all the aircraft family variants. The HoQ is a graphical tool, consisting of multiple matrices. It is used to translate the customers' needs (specified as 'whats') into engineering/technical characteristics (specified as 'hows') that help to meet or influence the customers' needs, aka voice of the customers (VOC). Table 2 shows the performance constraints, which are obtained from the HoQ. Here, the total number of constraints n_c is equal to 9, which will be used in Step 8 for down-selection. The fourth column in Table 2 shows the importance of performance constraints (in a scale of 1 to 10), which will be used in Step 9 for downselection of feasible design solutions.

Table 2 Constraints definitions for the three aircraft family variants

C_i	Parameter	Criteria	Imp	$(C)_S$	$(C)_B$	$(C)_L$
C_1	N_Pax	≥	10	150	170	190
C_2	Rng	≥	10	3500	3000	2500
C_3	TWR	≤	6	0.3	0.3	0.3
C_4	FASM	≤	9	0.07	0.07	0.07
C_5	TOFL	≤	6	6600	6900	7200
C_6	Vapp	≤	6	140	150	160

C_7	FONoise	≤	7	82	84	86
C_8	SLNoise	≤	7	82	84	86
C_9	NOx	≤	7	815	820	825

Step 2 - Generation of Initial Design Variables Sets: In this step, the HoQ is employed in order to map the performance constraints C_i (obtained in Step 1) into initial design variables sets V_i. Here, the 'hows' of the HoQ constructed in Step 1 (i.e. constraints) become the 'whats' of the new HoQ, and the 'hows' of the new HoQ (i.e. initial design variables sets) are identified which, as mentioned earlier, requires designers' experience and domain knowledge. Table 3 lists the initial design variables sets V_i i.e. Eq. (2), which are obtained from a notional HoQ. Here, the number of initial design variables sets, n_v, is equal to 16. The domains of the initial design variables sets $(D_i)_S$, $(D_i)_B$, and $(D_i)_L$ for the short, baseline and long variants, respectively, are shown in the last three columns of Table 3.

Table 3 Initial design variables sets for the three aircraft family variants

V_i	Symbol	$(D_i)_S$	$(D_i)_B$	$(D_i)_L$
V_1	L_F	[115.0 – 120.0]	[125.0 – 130.0]	[135.0 – 145.0]
V_2	S_W	[1300.0 – 1350.0]	[1325.0 – 1375.0]	[1350.0 – 1400.0]
V_3	AR_W	[8.0 – 11.0]	[8.0 – 11.0]	[8.0 – 11.0]
V_4	TCR_W	[0.10 – 0.11]	[0.10 – 0.11]	[0.10 – 0.11]
V_5	Phi_W	[24.0 – 26.0]	[24.0 – 26.0]	[24.0 – 26.0]
V_6	S_HT	[265.0 – 335.0]	[300.0 – 370.0]	[335.0 – 405.0]
V_7	AR_HT	[4.0 – 6.0]	[4.0 – 6.0]	[4.0 – 6.0]
V_8	TR_HT	[0.23 – 0.27]	[0.23 – 0.27]	[0.23 – 0.27]
V_9	Phi_HT	[28.0 – 30.0]	[28.0 – 30.0]	[28.0 – 30.0]
V_{10}	S_VT	[170.0 – 230.0]	[200.0 – 260.0]	[230.0 – 290.0]
V_{11}	AR_VT	[1.4 – 2.2]	[1.4 – 2.2]	[1.4 – 2.2]
V_{12}	TR_VT	[0.28 – 0.32]	[0.28 – 0.32]	[0.28 – 0.32]
V_{13}	Phi_VT	[33.0 – 35.0]	[33.0 – 35.0]	[33.0 – 35.0]
V_{14}	SLST	[25000.0 – 26000.0]	[27000.0 – 28000.0]	[29000.0 – 30000.0]
V_{15}	BPR	[6.0 – 8.0]	[6.0 – 8.0]	[6.0 – 8.0]
V_{16}	L_MLG	[117.0 – 120.0]	[117.0 – 120.0]	[117.0 – 120.0]

Step 3 - Aggregation and Discretization of Initial Design Variables Sets: In this step, the union operator, i.e. Eq. (5), is applied to the domains of initial design variables sets of the three aircraft family variants $(D_i)_S$, $(D_i)_B$, and $(D_i)_L$, given in Table 3. The resulting domains of aggregated design variables sets ${D_i}^+$ are shown in Table 4. All the initial design variables sets are continuous, therefore the domains of the aggregated design variables sets ${D_i}^+$ are discretized (linearly spaced between the lower and upper limits) in order to obtain a finite number of elements in the aggregated design variables sets. The domains ${D_i}^{d+}$ and cardinality p_i of the discretised aggregated design variables sets are shown in the last two columns of Table 4. This step does not stipulate any requirement on the cardinality of the discretized aggregated design variables sets p_i, although higher cardinality increases the time required for modelling and simulation.

Table 4 Aggregation and discretization of initial design variables sets

V_i	Symbol	D_i^+	D_i^{d+}	p_i
V_1	L_F	[115.0 – 145.0]	{115.0, 120.0, 125.0, 130.0, 135.0, 140.0, 145.0}	7
V_2	S_W	[1300.0 – 1400.0]	{1300.0, 1325.0, 1350.0, 1375.0, 1400.0}	5
V_3	AR_W	[8.0 – 11.0]	{8.0, 9.0, 10.0, 11.0}	4
V_4	TCR_W	[0.10 – 0.11]	{0.10, 0.11}	2
V_5	Phi_W	[24.0 – 26.0]	{24.0, 25.0, 26.0}	3
V_6	S_HT	[265.0 – 405.0]	{265.0, 300.0, 335.0, 370.0, 405.0}	5
V_7	AR_HT	[4.0 – 6.0]	{4.0, 4.5, 5.0, 5.5, 6.0}	5
V_8	TR_HT	[0.23 – 0.27]	{0.23, 0.25, 0.27}	3
V_9	Phi_HT	[28.0 – 30.0]	{28.0, 29.0, 30.0}	3
V_{10}	S_VT	[170.0 – 290.0]	{170.0, 200.0, 230.0, 260.0, 290.0}	5
V_{11}	AR_VT	[1.4 – 2.2]	{1.4, 1.6, 1.8, 2.0, 2.2}	5
V_{12}	TR_VT	[0.28 – 0.32]	{0.28, 0.30, 0.32}	3
V_{13}	Phi_VT	[33.0 – 35.0]	{33.0, 34.0, 35.0}	3
V_{14}	SLST	[25000.0 – 30000.0]	{25000.0, 26000.0, 27000.0, 28000.0, 29000.0, 30000.0}	6
V_{15}	BPR	[6.0 – 8.0]	{6.0, 7.0, 8.0}	3
V_{16}	L_MLG	[117.0 – 120.0]	{117.0, 120.0}	4

When improving existing passenger aircraft families, manufacturers (instead of pursuing clean-sheet design) try to maximize the reuse of existing aircraft family variants. For instance, Airbus launched the second generation of Airbus A320 family (i.e. A320neo family including A319neo, A320neo, and A321neo) which differs from the first generation primarily in using high bypass ratio engines while keeping the airframe and systems same. Accordingly, it is assumed that the empennage will be reused from the existing aircraft family. Therefore, the discretized aggregated design variables sets belonging to horizontal and vertical tails (V_6 to V_{13}) are reduced to a single fixed values, i.e. $p_i = 1, \forall i = 6, 13$. The values of the empennage parameters are listed in Table 5.

Table 5 Design parameters values for empennage

V_i	Symbol	Unit	Value
V_6	S_HT	ft^2	335.0
V_7	AR_HT	-	5.0
V_8	TR_HT	-	0.25
V_9	Phi_HT	deg	29.0
V_{10}	S_VT	ft^2	230.0
V_{11}	AR_VT	-	1.8
V_{12}	TR_VT	-	0.3
V_{13}	Phi_VT	deg	34.0

Step 4a - Generation of Major Components Sets: In this step, Design of Experiment (DOE) [38] is employed for generating the sets of major components, $MC_j,\ \forall\, j = 1, n_{mc}$. DOE is a statistical technique for sampling the design space in a systematic way. It enables the designer(s) to investigate the effects of multiple inputs on one or more outputs [39] which helps to better understand the design space when limited knowledge is available [40]. There are many sampling approaches for DOE. The simplest but most computationally expensive approach is the full factorial DOE [39] which requires discretization of the continuous aggregated design variables sets $V_i{}^{+}$. Other approaches e.g. Monte Carlo, fractional factorial, and Latin hypercube etc. [39] are more efficient compared to the full factorial DOE which do not require discretization, instead the designer needs to specify the number of elements in the major components sets MC_j . In the current case-study, full factorial DOE is used.

The major components include wing, fuselage, empennage (horizontal and vertical tails), engines, and landing gear. In this step, a set is generated for each of the major components by using Eq. (7). For instance, in Table 4, four discretized aggregated design variables sets ($V_2{}^{d+}$, $V_3{}^{d+}$, $V_4{}^{d+}$ and $V_5{}^{d+}$ with cardinalities $p_2 = 5$, $p_3 = 4$, $p_4 = 2$, and $p_5 = 3$, respectively) belong to wing. By using Eq. (7), i.e. the Cartesian product of $V_2{}^{d+}$, $V_3{}^{d+}$, $V_4{}^{d+}$ and $V_5{}^{d+}$, the set of wings MC_W may be created. This will result in the cardinality of the set of wings q_W equal to $p_2 \times p_3 \times p_4 \times p_5 = 5 \times 4 \times 2 \times 3 = 120$, calculated by using Eq. (8). In order to reduce the modelling and simulation activities, a single value for the wing sweep angle ($25deg$) is used. Therefore, the cardinality of the set of wings q_W is reduced to $p_2 \times p_3 \times p_4 \times p_5 = 5 \times 4 \times 2 \times 1 = 40$. After synthesis, the performance parameters such as mass and cost are evaluated using FLOPS.

It is important to note that most of the existing empirical computational models (found in literature) estimate the mass of wing (and other components) as function of Maximum Take-Off Weight (MTOW) [41]. These models are not suitable for aircraft family design because using a common major component will result in different mass of the component if the MTOW is different for the variants. In this research, computational models are used where the mass of the wing and other components is a function of only physical geometry parameters (such as S w, AR w, TR w, etc.), rather than MTOW [29].

Similarly, the set of fuselages MC_F is generated by using Eq. (7). In Table 4, only one discretized aggregated design variables set ($V_1{}^{d+}$ with cardinality $p_1 = 7$) belongs to fuselage. This results in the creation of the set of fuselage MC_F with cardinality q_F equal to 7. The set of empennage (horizontal and vertical tails) is reduced to one value. By using the design parameters listed in Table 5, the mass of the horizontal and vertical tails is calculated as

$1809.0lb$ and $1380.0lb$, respectively. Similarly, the sets of other major components (engine and landing gear) are generated by using Eq. (7). In Table 4, two discretized aggregated design variables sets (${V_{14}}^{d+}$ and ${V_{15}}^{d+}$ with cardinality $p_{14} = 6$ and $p_{15} = 3$) belong to engine, whereas only one discretized aggregated design variables set (${V_{16}}^{d+}$ with cardinality $p_{16} = 2$) belongs to landing gear. This results in the creation of the set of engine MC_E and landing gear MC_{LG} with cardinalities q_E and q_{LG} equal to $6 \times 3 = 18$ and 2, respectively. In order to reduce modelling and simulation, a single value of bypass ratio, i.e. ${V_{15}}^{d+} = 7.0$, is used. After synthesis, the performance parameters such as mass and cost are evaluated. It is important to note that performance evaluation may require inputs from teams synthesizing other components. For instance, the estimation of engine's Specific Fuel Consumption (SFC) requires the power off-take from all systems as input. Similarly, the estimation of landing gear mass requires the mass of all other components as input.

Step 4b - Generation of Systems Architectures Set: In this step, two enablers can be employed for the generation of systems architectures set: (a) morphological matrix and (b) function-means tree. The morphological matrix [42] [43], developed by Fritz Zwicky in 1943, is a tool for structuring the concept generation process and is supposed to encourage creativity. It provides a structured and systematic way of representing the decomposed functions (obtained using functional analysis as described in systems engineering standards [23] [24] [25] [26]) and the possible solutions to realize those functions. Although the morphological matrix provides a concise way of representing decomposed functions and their solutions, the dependency among different functions and solutions cannot be captured. Therefore, function-means tree [44] [45] can be employed which presents the functions and solutions/ means in a hierarchic manner, helping the designer(s) to create new architectures. It is important to note that both morphological matrix and function-means tree could also serve as a knowledge capturing tools.

As described in Section II, systems architecture is an ensemble of the architectures of all systems. Systems can be divided into two categories: power consumer and provider. Power consumer systems (i.e. Environmental Control System (ECS), Ice Protection System (IPS), Flight Control System (FCS), Fuel System (FS), and Landing Gear System (LGS)) need power to perform a particular function, whereas the function of power provider systems (e.g. Pneumatic Power System (PPS), Hydraulic Power System (HPS), and Electrical Power System (EPS)) is to generate and distribute power for the power consumer systems. Using the morphological matrix and function-means tree, a set of four systems architectures SA is generated, as shown in Table 6. In conventional systems architecture sa_1, all the three power provider systems (PPS, HPS, and EPS) are present, where PPS provides power to ECS and IPS, HPS provides power to FCS and LGS, and EPS provides power to FS and Misc. systems (such as avionics, instruments, lightings, in-flight entertainment and equipment). In the all-electric systems architecture, sa_4, only one power provider system (EPS) provides power to all power consumer systems. That is, all the consumer systems are operated by electrical power. The more-electric architectures sa_2 and sa_3 are in between conventional and all-electric architectures, where sa_2 replaces pneumatic with electrical power, and sa_3 replaces hydraulic with electrical power. By considering a set of systems architectures (conventional, more-electric, and all-electric), designer(s) are able to conduct trade-off between performance efficiency and risks.

Table 6 Set of systems architectures

Systems Architecture (SA)	Description	Power Provider Systems			Power Consumer Systems					
		PPS	HPS	EPS	ECS	IPS	FCS	FS	LGS	Misc.
sa_1	Conventional	Yes	Yes	Yes	PPS	PPS	HPS	EPS	HPS	EPS
sa_2	More-Electric	No	Yes	Yes	EPS	EPS	HPS	EPS	HPS	EPS
sa_3	More-Electric	Yes	No	Yes	PPS	PPS	EPS	EPS	EPS	EPS
sa_4	All-Electric	No	No	Yes	EPS	EPS	EPS	EPS	EPS	EPS

After synthesis, the impact parameters which include mass, power off-take (pneumatic and shaft power), ram drag, and costs are evaluated. The impact parameters of the systems architectures are obtained by aggregating the impact parameters of the individual systems. For instance, Table 7 shows the impact parameters (mass and power off-take) of the two systems architectures (sa_1 and sa_2). The total mass of sa_1 is $21735.9lb$, whereas the mass of sa_2 is $22110.8lb$ which is slightly higher. The conventional systems architecture (sa_1) requires $2.15kg/s$ pneumatic power and $159.4kW$ shaft power, whereas sa_2 requires no pneumatic power and $253.6kW$ shaft power. These systems architectures' impact parameters are used for performance evaluation at aircraft level. Although the mass and the required shaft power of ME architecture (sa_2) is higher compared to conventional architecture (sa_1), the efficiency of sa_2 may be higher at the aircraft level because the pneumatic power has far more severe impact on the Specific Fuel Consumption (SFC).

Table 7 Aggregation of systems architectures' impact parameters

	Systems Architecture 1, sa_1		Systems Architecture 2, sa_2	
Systems	Mass $[lb]$	Power	Mass $[lb]$	Power
ECS	1571.2	1.05 kg/s	1713.8	203.7 kW
IPS	201.3	1.10 kg/s	208.4	49.9 kW
FCS	2821.3	44.1 kW	2821.3	44.1 kW
FS	710.4	12.8 kW	710.4	12.8 kW
LGS	8507.3	24.3 kW	8732.5	24.3 kW
Misc.	7924.4	78.2 kW	7924.4	78.2 kW

Total	21735.9	2.15 kg/s 159.4 kW	22110.8	0 253.6 kW

Step 5 - Generation of Aircraft Set: After obtaining the major components sets (in Step 4a) and the systems architecture set (in Step 4b), the next step is to generate the set of aircraft A. Table 8 and Table 9 list the major components sets and systems architectures set, which were obtained in the previous steps.

Table 8 Sets of major components

j	Major Components Sets (MC_j)	q_j
1	Wings: $\{w_1, w_2, w_3, \dots, w_{40}\}$	40
2	Fuselages: $\{f_1, f_2, f_3, f_4, f_5, f_6, f_7\}$	7
3	Horizontal Tails: $\{ht_1\}$	1
4	Vertical Tails: $\{vt_1\}$	1
5	Engines: $\{e_1, e_2, e_3, e_4, e_5, e_6\}$	6
6	Landing Gears: $\{lg_1, lg_2\}$	2

Table 9 Set of systems architectures

Systems Architectures Set (SA)	n_{sa}
$\{sa_1, sa_2, sa_3, sa_4\}$	4

The elements in the set of aircraft $A = \{a_1, a_2, \dots, a_{n_a}\}$ are the individual aircraft which are obtained by applying the Cartesian operator, i.e Eq. 13) on the major components sets and systems architecture set. For instance, an aircraft a_1 can be created by combining the first element of each major components sets and systems architectures set, i.e. $a_1 = w_1 \times f_1 \times ht_1 \times vt_1 \times e_1 \times lg_1 \times sa_1$. The total number of aircraft n_a in the set of aircraft A can be obtained by using Eq. 14. As shown below, the total number of aircraft n_a that can be generated in this case is 13440.

After synthesis, the set of aircraft A can be analysed by evaluating the performance parameters through computational models. A screen capture of the AirCADia software is shown in Fig. 5, displaying the performance parameters of the aircraft set A in parallel coordinates plot. The later allows to visualize the multi-dimensional data in an effective way, where a design solution is represented as a polyline with vertices on the parallel vertical axes. In Fig. 5, each polyline represents an aircraft from the aircraft set A. Furthermore, the AirCADia software allows the designer(s) to interactively select an aircraft by clicking the polyline. For instance, user selected aircraft is represented by black polyline and the associated parameter values in Fig. 5. The performance parameters of the set of aircraft A can also be visualised as points in 2D scatter plots, as shown in Fig. 6(a), where the two performance parameters, i.e. gross weight (GW) and range (Rng), are displayed. In Fig. 6(a), the black rounded rectangle encloses the aircraft solutions which are non-dominated/ best (aka Pareto solutions) with respect to the gross weight (GW) and range (Rng). It is important to note that the Pareto solutions with respect to the GW and Rng may not be the best with respect to the other performance parameters. For instance, the same aircraft set A is also visualized in Fig. 6(b) and Fig. 6(c), where Fig. 6(b) shows the mission performance parameters, i.e. Take-Off Field Length (TOFL) and Fuel per Available Seat Mile (FASM), and Fig. 6(c) shows the environmental performance parameters, i.e. Fly-Over Noise (FONoise) and Nitrogen Oxide (NOx) emissions. The Pareto aircraft solutions with respect to the GW and Rng are also highlighted in Fig. 6(b) and Fig. 6(c). It can be seen that the highlighted aircraft solutions are not the Pareto solutions with respect to the TOFL, FASM, FONoise, and NOx.

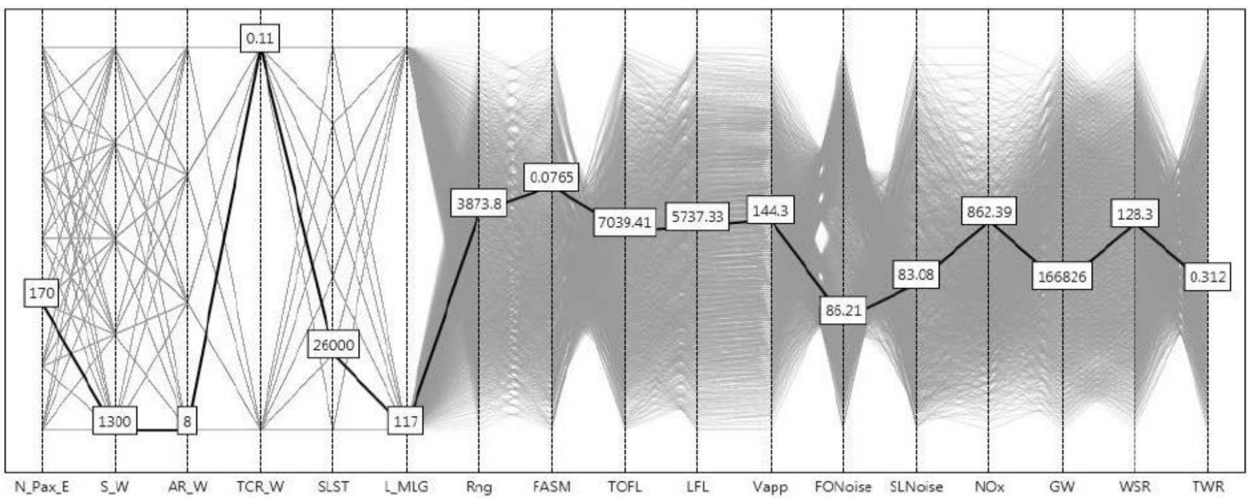

Fig. 5 Set of all aircraft, *A*, generated in this case study and shown in parallel coordinates plot

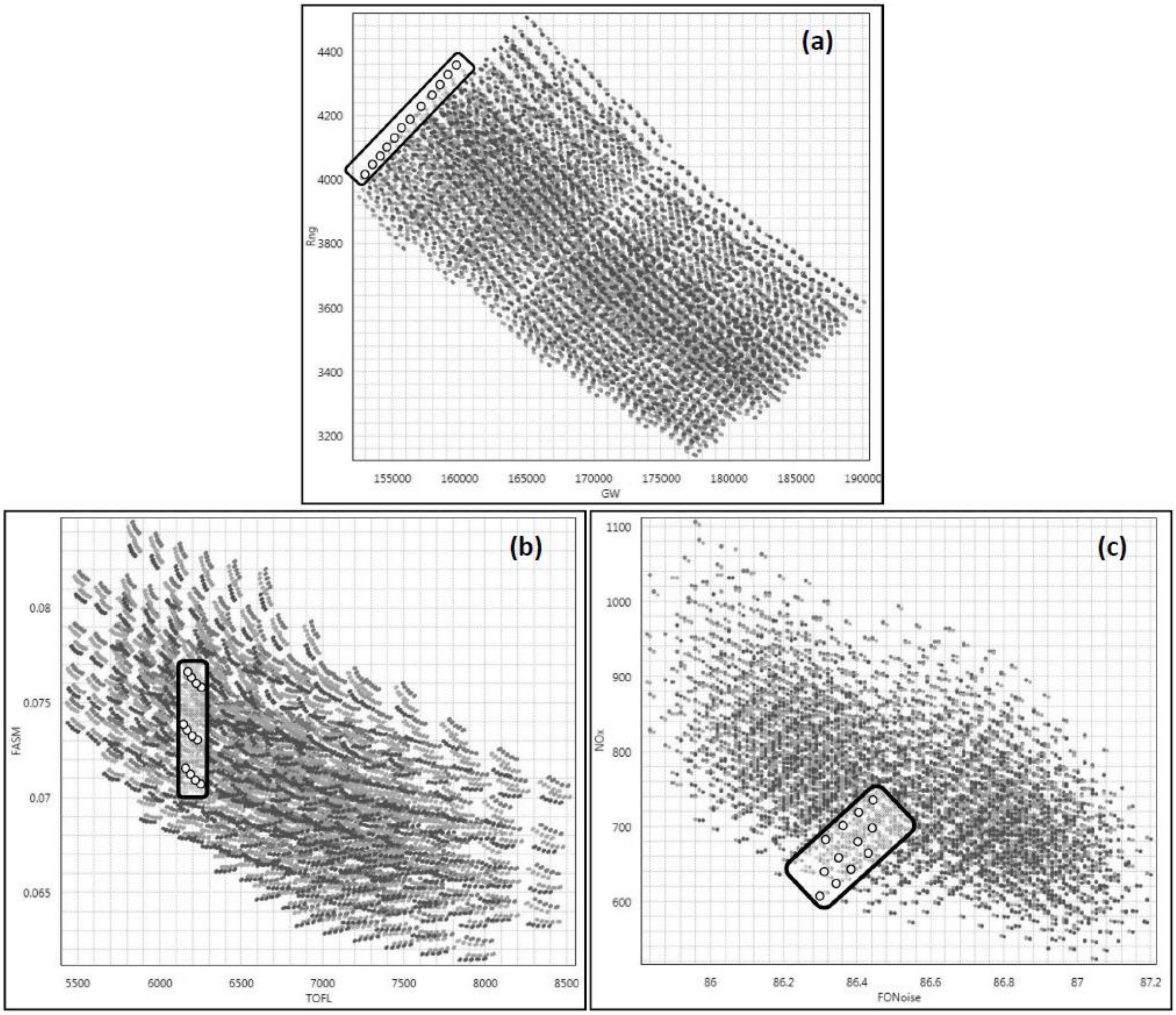

Fig. 6 Set of aircraft, A (scatter plots)

Step 6 - Classification of Aircraft Set into Aircraft Family Variants Sets: After the synthesis and analysis of the aircraft set A in Step 5, the next step is to classify the set of aircraft A (shown in Fig. 5) into aircraft family variants sets A_k, $\forall\, k = 1, n_{fv}$. The aircraft set A will be classified into three sets of aircraft A_S, A_B, and A_L corresponding to the short, baseline, and long variants, respectively. In this step, the classification operator, i.e. Eq. (16), is used. Here, the designer chooses which major components will be common or exclusive among the aircraft family variants. As shown in Table 10, wing, empennage (horizontal and vertical tails), and the landing gear are considered common among all the three family members, whereas the fuselage and the engines are considered exclusive.

Table 10 Common and exclusive major components

j	Major Component	Common/Exclusive
1	Wing	Common
2	Fuselage	Exclusive
3	Horizontal Tail	Common
4	Vertical Tail	Common
5	Engine	Exclusive
6	Landing Gear	Common

After choosing the common and exclusive major components among the aircraft family variants, the design variables sets belonging to the exclusive major components are categorized. Given the fuselage and the engines are considered exclusive, the design variables sets for the number of passengers N_Pax and sea-level static thrust SLST are divided into three subsets, as shown in Table 11 and Table 12. Hence, the number of common design variables sets n_{cv} is 4, whereas the number of exclusive design variables sets n_{sv} is 2. The selection of the minimum and maximum values used for the classification of design variables sets is arbitrary. The designers may choose other minimum and maximum values as appropriate.

Table 11 Exclusive discritized design variables sets

i	Parameter	Short ($k = 1$), p_{i_1}	Baseline ($k = 2$), p_{i_2}	Long ($k = 3$), p_{i_3}
1	N_Pax	{150, 160}, 2	{170, 180}, 2	{190, 200, 210}, 3
2	SLST	{25000, 26000}, 2	{27000, 28000}, 2	{29000, 30000}, 2

Table 12 Common discretized design variables sets

i	Parameter	Short/Baseline/Long	p_i
1	S_W	{1300, 1325, 1350, 1375, 1400}	5
2	AR_W	{8, 9, 10, 11}	4
3	TCR_W	{0.10, 0.11}	2
4	L_MLG	{117, 120}	2

The classification procedure is illustrated in Fig. 7, where the dashed-rectangles show the bounded regions of interest for the three aircraft family variants sets. It is important to note that the classification of the design variables sets reduces the total number of combinations for the design variables sets. For instance, the initial cardinality of the discretized aggregated design variables sets for the number of passengers N_Pax and sea-level static thrust SLST was 7 and 6, respectively, which makes the total $7 \times 6 = 42$ combinations (as shown by the 42 points in Fig. 7). The classification of the design variables sets results in 4 combinations for each of the short and baseline family members, and 6 combinations for the long variant. All other combinations (outside the bounded dashed-rectangles) of the number of passengers N_Pax and sea-level static thrust SLST are discarded, i.e. these combinations will not be considered for the generation of aircraft families in the next step. The total number of aircraft in the short, baseline, and long variants sets are 320, 320, and 480, respectively. Therefore, the number of aircraft in all three variants sets is reduced down to 1120 $(320 + 320 + 480)$ from $the\ total\ of$ 13440 generated in the previous step.

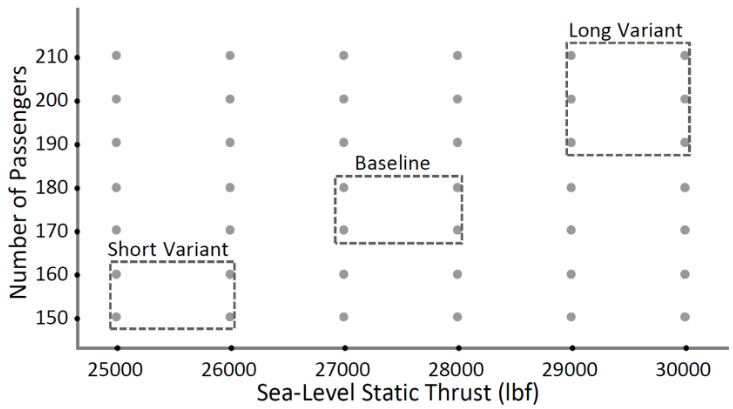

Fig. 7 Classification of aircraft sets

A screen capture of the AirCADia software is shown in Fig. 8, where the three aircraft family variants sets A_S, A_B, and A_L (obtained from classification) are displayed in a parallel coordinates plot.

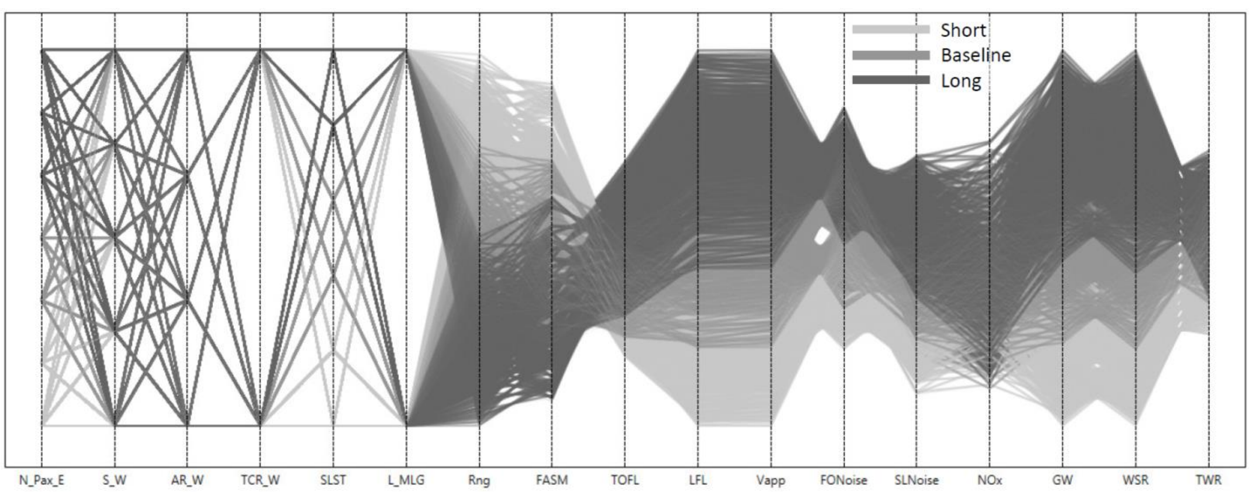

Fig. 8 The three sets of aircraft family variants

Step 7 - Generation of Aircraft Family Set: After the classification of the set of aircraft A into multiple aircraft family variants sets A_k, $\forall\ k = 1,\ n_{fv}$, the next step is to generate the set of aircraft families AF. The elements in the aircraft family set AF are the groups of aircraft depending on the number of aircraft family members. Here, a three-member aircraft family (short, baseline, and long variants) is considered to be designed (i.e. the number of family variants n_{fv} is equal to 3), therefore each element of the aircraft family set AF is a group of three aircraft which have common wing, empennage, and landing gear but exclusive fuselage and engines. In this step, the Cartesian operator (see Eq. 17), is applied on the three aircraft family variants sets (i.e. A_S, A_B, and A_L shown in Fig. 8) to generate the aircraft family set AF.

As the common systems architecture is used for all the variants when designing passenger aircraft families. The systems' components are, therefore, sized to meet the maximum requirements (i.e. for the largest family member). Table 11 and Table 12 show the common and exclusive discretized design variables sets and their cardinalities that can be used to determine the total number of aircraft families. By using Eq. 18, the total number of aircraft families n_{af} is 30720, as shown below. Here, the number of common design variables sets n_{cv} is 4, the number of exclusive design variables sets n_{ev} is 2, and the number of aircraft family variants n_{fv} is 3.

$$\begin{gathered} n_{af} = n_{sa} \cdot \prod_{i=1}^{n_{cv}} p_i \cdot \prod_{i=1}^{n_{ev}} \prod_{k=1}^{n_{fv}} p_{i_k} \\ n_{af} = p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot (p_{1_1} \cdot p_{1_2} \cdot p_{1_3}) \cdot (p_{2_1} \cdot p_{2_2} \cdot p_{2_3}) \\ n_{af} = 4 \cdot 5 \cdot 4 \cdot 2 \cdot 2 \cdot (2 \cdot 2 \cdot 3) \cdot (2 \cdot 2 \cdot 2) = 30720 \end{gathered} \tag{19}$$

Step 8 - Down-Selection through Constraint Satisfaction: In this step, constraint satisfaction is applied in order to discard the infeasible aircraft family solutions. Apart from the performance constraints defined in Step 1, other criteria (e.g., compatibility constraints, design for manufacture and assembly, etc.) are used in this step to discard infeasible aircraft family solutions. It is important to note that if the number of passengers (or any other) requirement changes during the design process, the designer(s) would still be able to change the constraint value without performing new sizing/evaluation studies. Here, the maximum number of passengers (N_Pax) is selected arbitrarily for the aircraft family variants, i.e. 160, 180, and 210 for the short, baseline, and long variants, respectively. The designer(s) may choose other values depending on the market requirements. The side-views of the three aircraft family variants with the selected number of passengers (N_Pax) are shown in Fig. 9, where the landing angle was obtained from simple geometrical/parametric calculations .

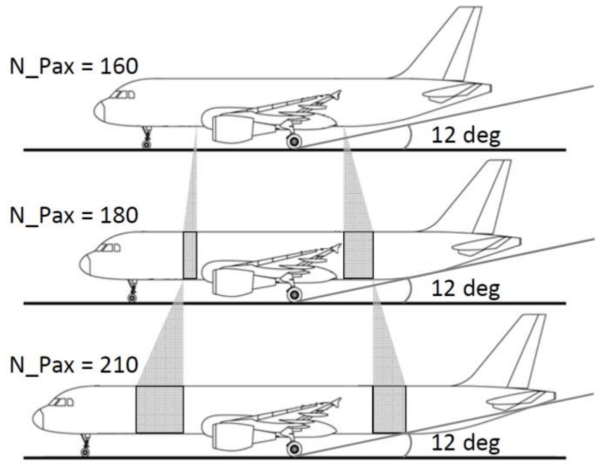

Fig. 9 Landing angle of the three aircraft family variants

In Fig. 9, the lower value of the landing gear length ($117in$) is used for all the three aircraft variants. Although the lower landing gear length reduces the gross weight of the aircraft (i.e. increases the fuel efficiency), it does not satisfy the landing angle constraint (required for take-off and landing) of $12deg$ for the long aircraft variant, as shown in Fig. 9. In addition, it does not provide enough room for the higher bypass ratio engines due to insufficient ground clearance. Therefore, the set of landing gears length (L_MLG) was reduced to higher value i.e. $120in$. Furthermore, in order to provide higher thrust-to-weight ratio and meet the top-of-the-climb thrust requirements, the higher values for the sea-level static thrust (SLST) are used for all the aircraft variants, i.e. 26000, 28000, and 30000 for the short, baseline, and long variants, respectively.

Another example of constraint satisfaction is shown in Fig. 10. Depicted are the feasible regions (in white) with respect to wing design variables, i.e. S_W and AR_W for the baseline aircraft variant with regard to each of the four systems architectures in SA.. The values for each constraint are the same in the four plots. However, the differences between the individual feasible regions are due to the different performance efficiencies of the respective systems architectures. For brevity, the rest of the down-selection described below is performed only for the conventional (sa_1) and the more-electric systems architecture (sa_2)

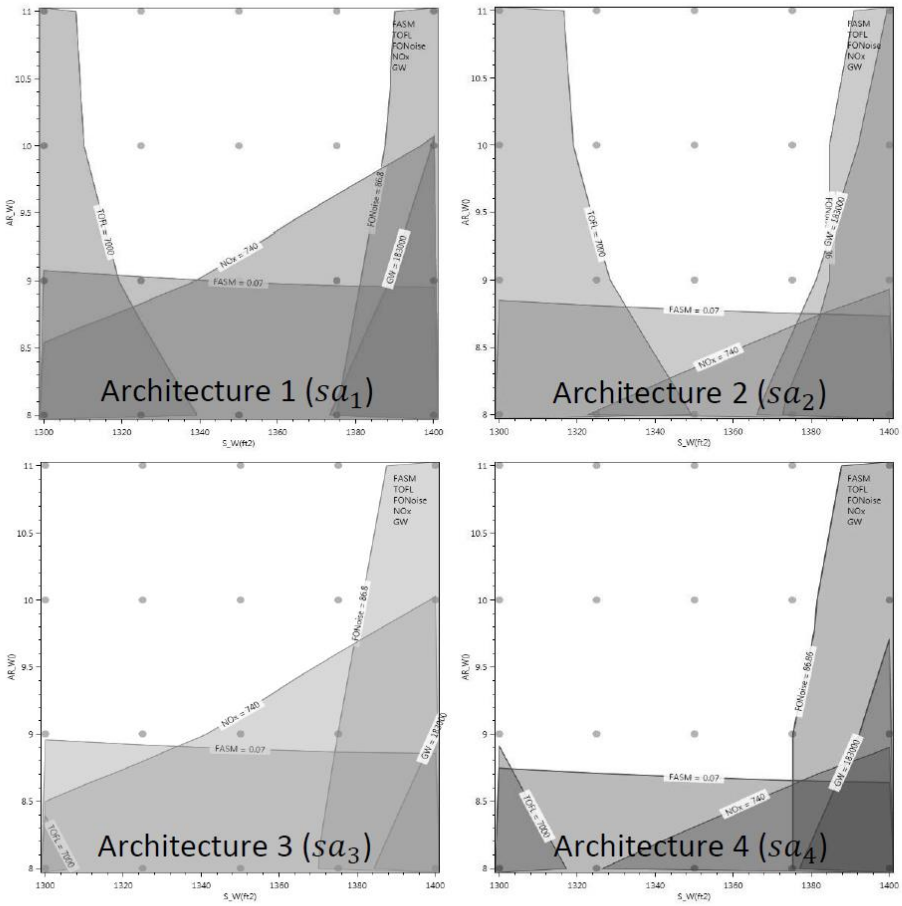

Fig. 10 Baseline aircraft variant with four systems architectures

Shown in Fig. 11 are the feasible regions (with respect to S_W and AR_W) of the three aircraft family variants (short, baseline, and long) with conventional systems architecture, sa_1. Here, the constraint values are different in the three plots, due to the different performance requirements of the three aircraft family variants. Similarly, the feasible regions of the three aircraft variants with regard to sa_2 are shown in Fig. 12.

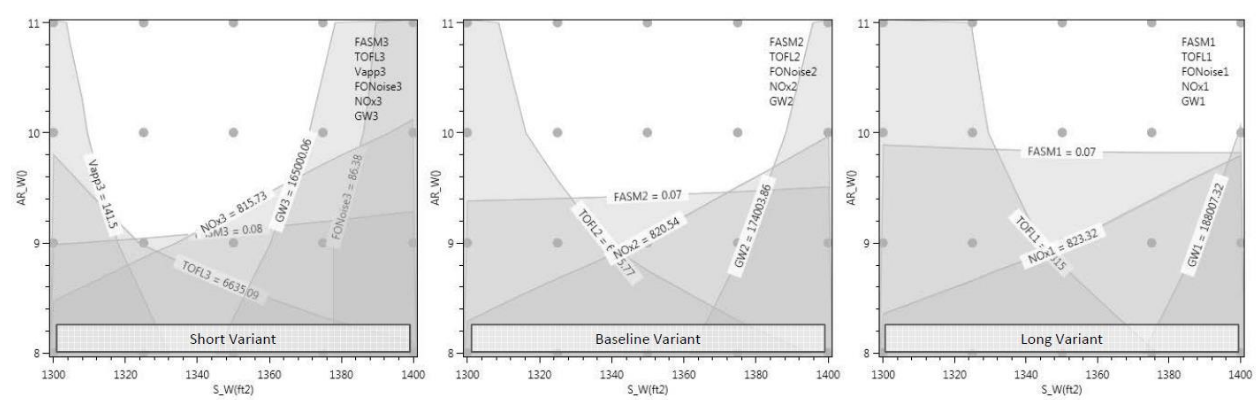

Fig. 11 Constraint satisfaction for the three family variants with conventional systems architecture, sa_1

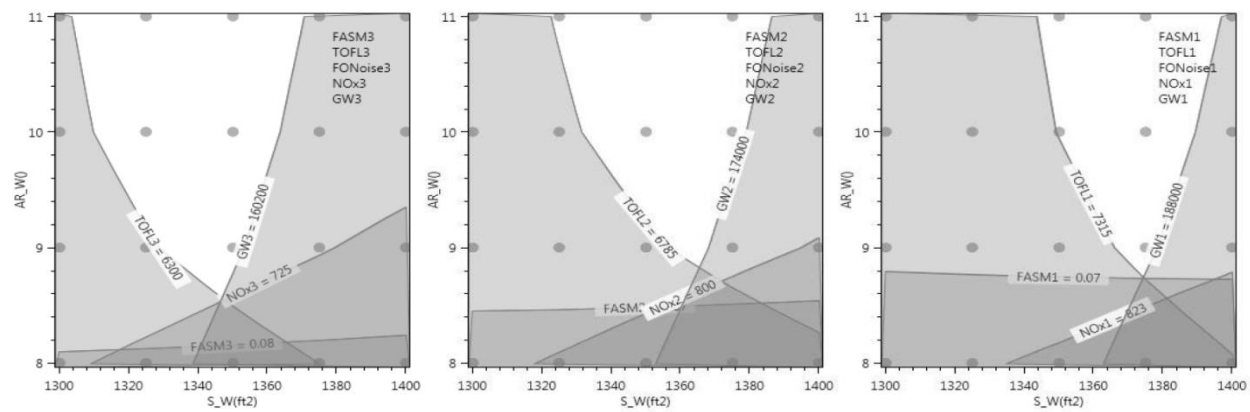

Fig. 12 Constraint satisfaction for the three family variants with more-electric systems architecture, sa_2

The intersection of the three feasible sets (regions) in Fig. 11 and Fig 12 are shown in Fig. 13(a) and Fig. 13(b), respectively. That is, the intersected (hashed) regions represent the feasible regions with respect to all the family variants requirements for the conventional (sa_1) and the more-electric (sa_2) systems architectures.

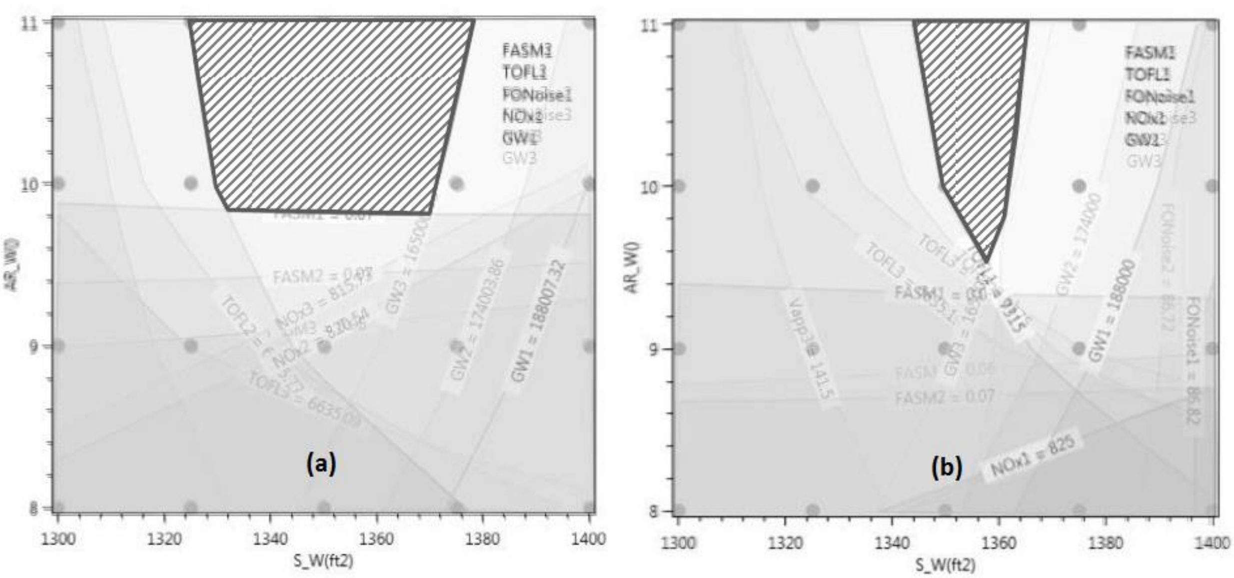

Fig. 13 Intersected regions of three family variants with (a) conventional systems architecture, sa_1 and (b) more-electric systems architecture, sa_2

Once the set intersection of the three aircraft family variants for each of the systems architectures is obtained, the intersection of all architectural sets can be obtained. In this example, the intersection of the feasible regions in Fig. 13(a) and Fig. 13(b) is shown in Fig. 14 and is represented by the doted region. The result shown so far have been obtained for a constant thickness-to-cord ratio of 0.11, which is one of values of the (input) design parameter sets. Fig. 15 shows the overall set intersection, but with thickness-to-cord ratio of 0.10. The feasible region is larger due mainly to lower drag.

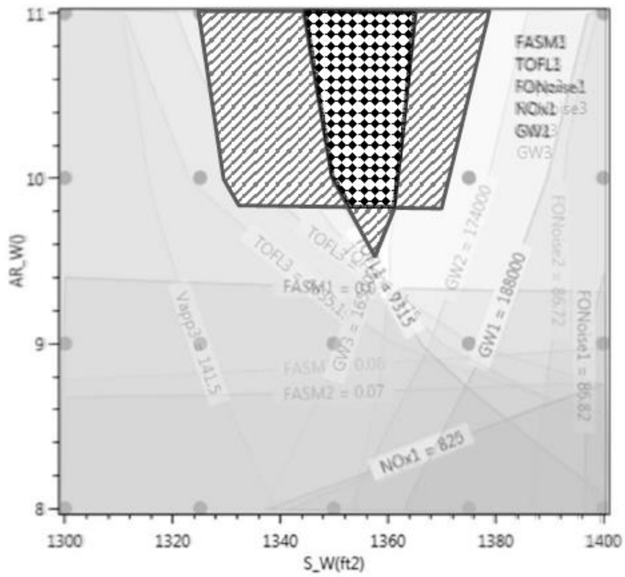

Fig. 14 Feasible intersected set (region) for the family variants with systems architectures sa_1 and sa_2 (TCR_W = 0.11)

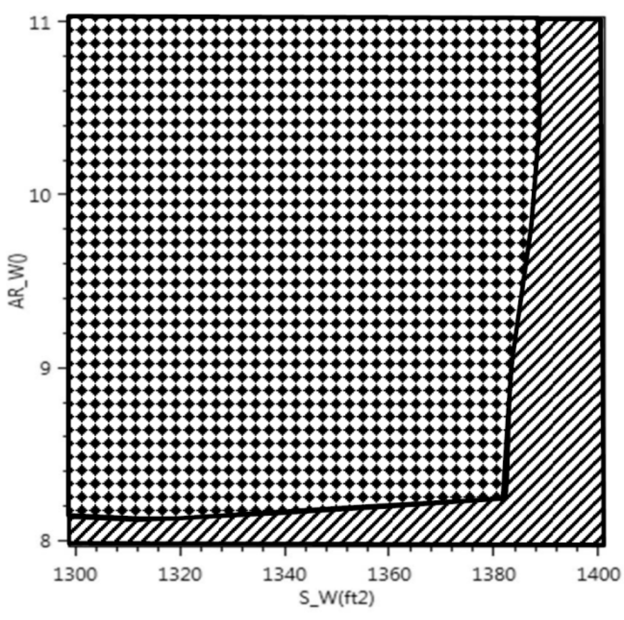

Fig. 15 Feasible intersected set (region) for the family variants with systems architecture sa_1 and sa_2 (TCR_W = 0.10)

The results shown in Fig. 14 and Fig. 15 illustrate one of the main potential benefits of the proposed approach. Namely, if the wing design is selected from the doted region it will be feasible with regard to all architectures considered. This in turn is expected to reduce the risk related to airframe-systems integration and to offer more scope for innovation.

Step 9 - Down-Selection through Ranking: After applying all constraints, the reduced design variable sets, shown as unfilled dots in Fig. 16, are further narrowed down by utilizing a non-dominated filtering.

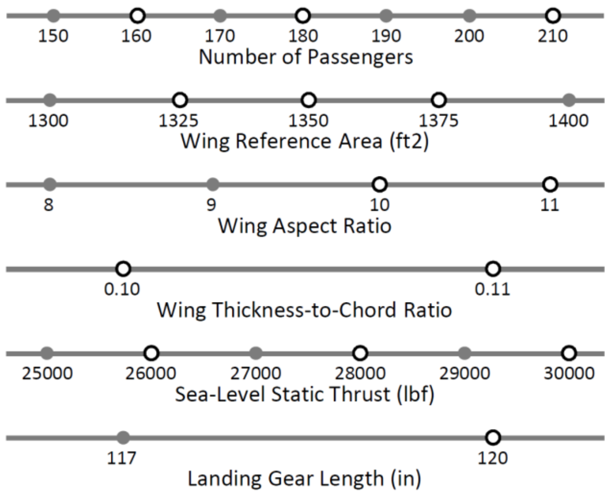

Fig. 16 Reduced design variables sets

Multi-criteria decision making methods such as TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) [46], can be employed to rank the remaining feasible aircraft family solutions.

It is important to note that the proposed methodology is expected to reduce the nugatory design iterations. However, there may be cases when a null (empty) set is the result of the feasible set intersections described above. This may require either modifying the initial design variables sets or relaxing the constraints. Negotiating the constraints may not require further synthesis and analysis activity, but modifying the initial design variables sets (bounds) will lead to new design iterations.

IV. Evaluation

This section is concerned with the evaluation of the proposed methodology, which is performed by means of qualitative assessment. First, in order to compare the proposed methodology with the traditional Point-Based Design (PBD) approach, the same application case-study (described in Section III) was executed with the PBD approach.

Next, the application case-study and the two approaches were presented to a panel of industrial experts (from airframe and engine manufacturer companies) who were asked to comment on the merits and potential challenges of the proposed methodology.

A. Traditional PBD Approach Implementation

As mentioned earlier, the traditional PBD approach employs sequential, optimization-based methods where a single design concept is selected quite early in the design phase (after brainstorming or utilizing past experience), which is then subsequently tweaked/modified until it satisfies all the requirements. This approach is highly iterative and can lead to convergence problems when designing complex innovative products.

For comparison purposes, the same set of computational models and tools were used to execute the PBD approach. A hypothetical scenario is used to demonstrate the traditional PBD approach, as follows. It is assumed that a decision was made early in the design phase to use an all-electric systems architecture for all the three variants of aircraft family. The expected benefits are reduced mass and fuel burn due to removing hydraulic and pneumatic (bleed) power systems. Therefore, instead of using hydraulic actuators for Flight Control System (FCS) and Landing Gear System (LGS), it was decided to use Electro Mechanical Actuators (EMAs) for FCS and LGS. Similarly, instead of using bleed air for Environmental Control System (ECS) and Ice Protection System (IPS), it was decided to use ram air with electric compressors for ECS and electro-thermal mats for IPS. After formulating and setting the optimization problem, NSGAII [28] genetic algorithm was used to obtain the results. For brevity, the results listed below cover only the baseline variant of the aircraft family. The key parameters are shown in the first row (Iteration 0) of Table 13.

Table 13 Design iterations in traditional point-based approach

Iterations	S_W	TCR_W	SLST	BPR	L_MLG	FuelCap	Fuel	MTOW	TOFL ≤ 6725	SLNoise ≤ 85	NOx ≤ 775
Iteration 0	1320	0.10	29000	6.0	115.2	43320	42629.0	168901.3	6643	84.3	729.1
Iteration 1	1320	0.10	29000	6.0	115.2	43320	42663.8	169057.2	6653	84.4	729.7
Iteration 2	1320	0.11	29000	6.0	115.2	43220	44093.3	169922.6	6714	84.6	751.9
Iteration 3	1320	0.11	29000	6.0	115.2	46000	44143.6	170138.1	6729	84.7	752.7
Iteration 4	1320	0.11	30000	6.0	115.2	46000	44924.8	170970.9	6560	85.6	765.5
Iteration 5	1320	0.11	30000	7.0	115.2	46000	44255.6	170205.4	6571	84.2	753.8
Iteration 6	1320	0.11	30000	7.0	117.8	46000	45409.8	171548.3	6687	84.8	767.8

Iteration 1: The resulting design for baseline variant (featuring high aspect ratio in order to reduce airframe noise) satisfied all the constraints considered during the optimization process. Later, during the analysis phase, it

was pointed out that elimination of the Hydraulic Power System (HPS) may cause thermal issues with Electro Mechanical Actuators (EMAs), since the hydraulic fluid used in HPS provides a convenient means of transporting and dissipating the heat generated by the actuation system. Initial analysis confirmed that the natural radiation and convention is not sufficient to keep the EMAs at acceptable operating temperature. It was, therefore, decided to install a dedicated thermal management system (Heat Pipes) for EMAs. The heat pipes imposed additional mass of $105.2lb$. The sizing was conducted for the new mass, which resulted in a slight increment of block fuel and MTOW, as shown in the second row (Iteration 1) of Table 13 where block fuel and MTOW have increased from $42629.0lb$ to $42663.8lb$ and $168901.3lb$ to $169057.2lb$, respectively. The penalty for adding heat pipes was low; all the performance constraints considered during optimization were still satisfied.

Iteration 2: Although adding heat pipes solved the thermal issues with EMAs with small penalty on block fuel and MTOW, it was discovered later during the integration phase that the assembly of EMA and heat pipes was not fitting inside the wing profile for aileron EMA. At this point, the team started to consider switching back to hydraulic actuators. An assessment study was initiated and it was found that the design rework required introducing HPS and switching EMAs to hydraulic actuators was the same as the work required for the new or clean-sheet design because almost every system was being affected. It was, therefore, decided to solve this issue by increasing the thickness-to-chord ratio of the wing TCR_W (rather than switching to hydraulic actuators). The increment of TCR_W from 0.10 to 0.11 was sufficient to fit the whole assembly (EMA and heat pipe) in the aileron. The results of the new study (initiated by increased TCR_W) are shown in the third row (Iteration 2) of Table 13. The increment of TCR_W resulted in adverse effects on block fuel and MTOW.

Iteration 3: Increasing the TCR_W solved the EMA and heat pipe assembly fitting problem, but the required block fuel to achieve $3000.0nm$ range was increased from $42663.8lb$ to $44093.3lb$. This resulted into another problem; the total fuel capacity of the fuel tanks $43220lb$ turned out to be less than the required fuel to achieve the mission range. It was then decided to redesign the center (fuselage) fuel tank to increase the fuel capacity, as the wing fuel tanks capacity could not be increased. The new study was set-up and the results are shown in the fourth row (Iteration 3) of Table 13. The increment of TCR_W and fuel tank capacity increased the MTOW from $168257.2lb$ to $170138.1lb$.

Iteration 4: Although increasing the fuel tank capacity solved the fuel problem, the resulting MTOW (from increased TCR_W and fuel tank capacity) was increased to a point where the maximum take-off field length constraint becomes active. As shown in the fourth row of Table 13, the resulting Take-Off Field Length (TOFL) was $6729.0ft$ which is higher than the constraint value (i.e. $6725.0ft$). This problem was solved by initiating another study where the Sea-Level Static Thrust (SLST) was increased from $29000.0lb$ to $30000.0lb$. The results of this new study are shown in the fifth row (Iteration 4) of Table 13 where the TOFL was decreased from $6729.0ft$ to $6560.0ft$, hence satisfying the TOFL constraint.

Iteration 5: Increasing the SLST solved the issue with the TOFL constraint, but resulted in the violation of sideline noise constraint. As shown in the fifth row of Table 13, the resulting sideline noise was $85.6dB$ which is higher than the constraint value (i.e. $85.0dB$). In order to reduce the combined sideline noise, it was decided by the team to increase the Bypass Ratio (BPR). Another new study was initiated where the BPR values was increased from 6.0 to 7.0. The results of this new study are shown in the sixth row (Iteration 5) of Table 13.

Iteration 6: Although increasing the BPR resolved the issue with sideline noise constraint, it was discovered later during the integration phase that the engine ground clearance is not sufficient due to the higher nacelle diameter, resulting from the increased BPR. In order to rectify this problem, another study was initiated where the main landing gear length L_MLG was increased from $115.2in$ to $117.8in$. The results of this study are shown in the seventh row (Iteration 6) of Table 13. The increment of L_MLG also increased the landing gear mass, and the resulting MTOW was increased from $170205.4lb$ to $171548.3lb$. All the performance constraints were satisfied by the design after six iterations, but the new design performance was not as good as compared to the original design before design rework iterations. The block fuel was increased from $42629.0lb$ to $45409.8lb$ (increment of 6.5 %), and the MTOW was increased from $168901.3lb$ to $171548.3lb$ (increment of 1.6%).

The variations due to the design rework/iterations in the MTOW, block fuel, and TOFL are plotted in Fig. 17, where the two horizontal lines show the constraint values.

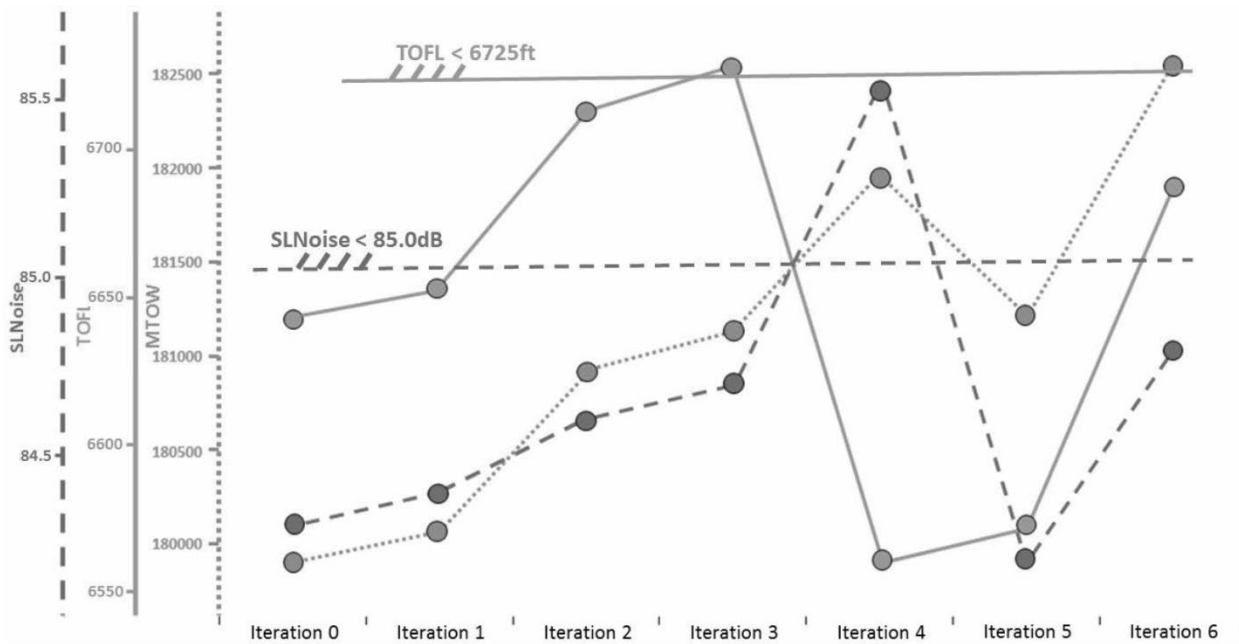

Fig. 17 Variations in MTOW, TOFL, and SLNoise during design iterations

It should be noted that if the proposed approach was used, the available feasible solutions with higher thickness-to-cord ratio (Fig. 14) would have been able to accommodate the change and thus eliminate the substantial iterations described above. .

B. Experts Feedback

The application case-study and the two approaches (proposed methodology and traditional PBD approach) were presented to a panel of industrial experts (from airframe and engine manufacturer companies) who were asked to comment on the merits and potential challenges of the proposed methodology. In particular, experts were asked to comment on the benefits of the proposed aircraft family design methodology compared to traditional/current approach used in the industry, the associated challenges, and the possibility to introduce it in the organization's design process with relative ease. The flexibility for handling changing design requirements and the ability to conduct trade-off between sets of systems architectures early in the conceptual design stage were also discussed. The panel observed several advantages of the proposed methodology relative to the current industrial design strategy. In particular, it was agreed on the whole that the proposed methodology would offer:

- An interactive exploration of a wider design space to discover creative solutions.

- Identification of several feasible/satisfactory solutions, providing more freedom of choice (for designers) and reducing design iterations.
- A repository of backup design options for meeting changing requirements without additional design overhead.
- An environment (for designers) to foster innovation by considering systems architectures analysis and design at the aircraft level, allowing to bring more design knowledge early into the conceptual stage.

It was pointed out that the proposed methodology provides potentially great development advantages when used for designing innovative aircraft families, requiring many design iterations. It reduces the risks of design rework and increases the probability of success in finding best/optimal solution by delaying the critical decisions when more design knowledge is available. The panel identified that the proposed methodology still faces a challenge from a (computational/human) resources point of view during detailed design stages where it would be difficult to maintain and carry forward many design solutions together.

V. Conclusion

Presented in this paper is a novel methodology for the design of passenger aircraft families at the early design stage. The proposed method embraces the principles of the Set-Based Design (SBD) in which the design is kept open by the parallel development of multiple design solutions and where the designer focuses on eliminating the inferior alternatives rather than on committing to a single option. The evaluation of the proposed methodology has been conducted with an application test case of a three-member aircraft family design and presenting it to a panel of industrial experts who were asked to comment on the merits and potential challenges of the approach. The findings indicate that the proposed methodology is expected to enable the designers to better utilize their experience/knowledge and also offers a more thorough and systematic exploration of the design space and identification of several feasible/satisfactory solutions, providing more freedom of choice. By considering early systems architectures analysis and design at the aircraft level, the proposed methodology provides an environment where designers can foster innovation. Additionally, the proposed approach offers a repository of backup design options for meeting changing requirements without additional design activity. While the demonstrated enablers are reaching a stage of sufficient maturity allowing a multitude of design solutions including systems architectures to be synthesized and analyzed rapidly and simultaneously, this still is expected to present a challenge from a computational/human) resources point of view.

Future work will extend the proposed approach to account for the significant uncertainties associated with early design and will explore the incorporation of methods for design rationale capture.

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References

[1] Simpson, T. W., Siddique, Z., and Jiao, R. J., *Product platform and product family design: methods and applications*, Springer, 2006.

[2] Funk, J. E., Harber, J. R., and Morin, L., "Future Military Common Aircraft Development Opportunities," *44th AIAA Aerospace Sciences Meeting and Exhibit*, 9 - 12 January 2006.

[3] Willcox, K. and Wakayama, S., "Simultaneous Optimization of a Multiple-Aircraft Family," *Journal of Aircraft*, Vol. 40, No. 4, 2003, pp. 616–622.

[4] Zhuravlev, P. and Zhuravlev, V., "Significance of modifications for development of passenger airplanes," *Aircraft Engineering and Aerospace Technology*, Vol. 84, No. 3, 2012, pp. 172–180.

[5] Romli, F. I., *A strategic planning methodology for aircraft redesign*, Pro-Quest, 2009.

[6] Nunez, M. and Guenov, M. D., "Design-Exploration Framework for Handling Changes Affecting Conceptual Design," *Journal of Aircraft*, Vol. 50, No. 1, 2013, pp. 114–129.

[7] Cabral, L. V. and Paglione, P., "Conceptual design of families of aircraft using multi objective design optimization theory and genetic algorithm techniques," *6th World Congresses of Structural and Multidisciplinary Optimization*, 30 May - 03 June 2005.

[8] D'Souza, B. and Simpson, T. W., "A genetic algorithm based method for product family design optimization," *Engineering Optimization*, Vol. 35, No. 1, 2003, pp. 1–18.

[9] Allison, J., Roth, B., Kokkolaras, M., Kroo, I., and Papalambros, P. Y., "Aircraft family design using decomposition-based methods," *Proceedings of the 11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2006.

[10] Roth, B. D., *Aircraft family design using enhanced collaborative optimization*, ProQuest, 2008.

[11] Ullman, D. G., *The Mechanical Design Process*, McGraw-Hill, Boston, Mau., 3rd ed., 2003.

[12] "Boeing firms up 737 replacement studies by appointing team," 2006.

[13] O'Keeffe, N., "Caution welcomed: Boeing 737 Max," 2011.

[14] Scholz, D., "Aircraft Systems Reliability, mass Power and Costs," *European Workshop on Aircraft Design Education*, 2002.

[15] Moir, I. and Seabridge, A., *Aircraft Systems: Mechanical, electrical and avionics subsystems integration*, John Wiley & Sons, West Sussex, England, 3rd ed., 2008.

[16] Dornheim, M. A., "Electric Cabin," *Aviation Week & Space Technology*, Vol. 162, No. 13, 03/28 2005, pp. 47–50.

[17] Sobek, D. K., Ward, A. C., and Liker, J. K., "Toyota's principles of set based concurrent engineering," *Sloan management review*, Vol. 40, No. 2, 1999, pp. 67–84.

[18] Singer, D. J., Doerry, N., and Buckley, M. E., "What Is Set-Based Design?" *Naval Engineers Journal*, Vol. 121, No. 4, 2009, pp. 31–43.

[19] Kennedy, B. M., Sobek, D. K., and Kennedy, M. N., "Reducing Rework by Applying Set Based Practices Early in the Systems Engineering Process," *Systems Engineering*, Vol. 17, No. 3, 2014, pp. 278–296.

[20] Nahm, Y.-E. and Ishikawa, H., "Novel space-based design methodology for preliminary engineering design," *The International Journal of Advanced Manufacturing Technology*, Vol. 28, No. 11-12, 2006, pp. 1056–1070.

[21] Khan, M., Al-Ashaab, A., Doultsinou, A., Shehab, E., Ewers, P., and Sulowski, R., *Set-Based Concurrent Engineering process within the LeanPPD environment*, Improving Complex Systems Today, Springer, 2011, pp. 433–440.

[22] Davies, M., *The standard handbook for aeronautical and astronautical engineers*, McGraw-Hill, 2003.

[23] "ANSI/EIA 632, Process for engineering a system," 1998.

[24] "ISO/IEC 15288, Systems and software engineering - System life cycle processes," 2008.

[25] INCOSE, *Systems Engineering Handbook*, INCOSE-TP-2003-002-03.2. 2., v.3.2.2 ed., 2011.

[26] Kapurch, S. J., *NASA Systems Engineering Handbook*, DIANE Publishing, 2010.

[27] Nunez, M., Datta, V. C., Molina-Cristobal, A., Guenov, M., and Riaz, A., "Enabling exploration in the conceptual design and optimisation of complex systems," *Journal of Engineering Design*, Vol. 23, No. 10-11, 2012, pp. 852–875.

[28] Deb, K., Agrawal, S., Pratap, A., and Meyarivan, T., "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II," *Lecture notes in computer science*, Vol. 1917, 2000, pp. 849–858.

[29] McCullers, L. A., "Flight Optimization System", User's Guide, Release 8.23, NASA Langley Research Center, 2011.

[30] Meier, O. and Scholz, D., "A Handbook Method for the Estimation of Power Requirements for Electrical De-Icing Systems," in "Deutscher Luft-und Raumfahrtkongress 2010," Hamburg, Germany, 2010.

[31] Chakraborty, I., Trawick, D., Mavris, D.N., "A Requirements-driven Methodology for Integrating Subsystem Architecture Sizing and Analysis into the Conceptual Aircraft Design Phase," *14th AIAA Aviation Technology, Integration, and Operations Conference*, 16-20 June 2014, Atlanta, GA.

[32] Guenov, M. D., Nunez, M., Molina-Cristobal, A., Datta, V. C., and Riaz, A., "AirCADia – An interactive tool for the composition and exploration of aircraft computational studies at early design stage," *29th Congress of the International Council of the Aeronautical Sciences*, 7 - 12 September 2014.

[33] Warwick, G., “Choose the Future,” *Aviation Week & Space Technology*, Vol. 173, No. 26, 07/18 2011, pp. 44–44.

[34] Rosero, J. A., Ortega, J. A., Aldabas, E., and Romeral, L., “Moving towards a more electric aircraft,” *Aerospace and Electronic Systems Magazine, IEEE*, Vol. 22, No. 3, 2007, pp. 3–9.

[35] Sinnett, M., “787 No-Bleed Systems: Saving Fuel and Enhancing operational Efficiencies,” 2007.

[36] Bossche, D. V. D., “The A380 flight control electro hydrostatic actuators, achievements and lessons learnt,” *25th Congress of the International Council of the Aeronautical Sciences*, September 2006.

[37] Hauser, J. R. and Clausing, D., “The house of quality,” *Harvard Business Review*, Vol. 66, No. May-June, 1988, pp. 63–73.

[38] Myers, R. H., Montgomery, D. C., and Anderson-Cook, C. M., *Response surface methodology: process and product optimization using designed experiments*, Vol. 705, John Wiley & Sons, 2009.

[39] Antony, J., *Design of experiments for engineers and scientists*, Elsevier, 2014.

[40] Montgomery, D. C., *Design and analysis of experiments*, John Wiley & Sons, 2008.

[41] Torenbeek, E., *Advanced Aircraft Design: Conceptual Design, Technology and Optimization of Subsonic Civil Airplanes*, John Wiley & Sons, 2013.

[42] Zwicky, F., *The morphological method of analysis and construction*, California institute of technology, 1948.

[43] lvander, J., Lundn, B., and Gavel, H., “A computerized optimization framework for the morphological matrix applied to aircraft conceptual design,” *Computer-Aided Design*, Vol. 41, No. 3, 2009, pp. 187–196.

[44] Andreasen, M. M., Machine design methods based on a systematic approach contribution to a design theory, Ph.D. thesis, Lund University, Sweden, 1980.

[45] Hansen, C. T., “An approach to simultaneous synthesis and optimization of composite mechanical systems,” *Journal of Engineering Design*, Vol. 6, No. 3, 1995, pp. 249–266.

[46] Lai, Young-Jou, Ting-Yun Liu, and Ching-Lai Hwang. "Topsis for MODM" *European Journal of Operational Research*, Vol. 76, No.3, 1994, pp. 486-500.