**CRANFIELD UNIVERSITY**

Atif Riaz

# A Set-Based Approach to Passenger Aircraft Family Design

SCHOOL OF AEROSPACE, TRANSPORT
AND MANUFACTURING

PhD
Academic Year: 2014 - 2015

Supervisor: Prof Marin D. Guenov
December 2015

**CRANFIELD UNIVERSITY**

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD

Academic Year: 2014 - 2015

Atif Riaz

# A Set-Based Approach to Passenger Aircraft Family Design

Supervisor: Prof Marin D. Guenov

December 2015

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

# Declaration of Authorship

I, Atif Riaz, declare that this thesis titled, 'A Set-Based Approach to Passenger Aircraft Family Design' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

# Abstract

In today's highly competitive civil aviation market, aircraft manufacturers develop aircraft families in order to satisfy a wide range of requirements from multiple airlines, with reduced costs of ownership and shorter lead time. Traditional methods for designing passenger aircraft families employ a sequential, optimisation-based approach, where a single configuration and systems architecture is selected fairly early which is then iteratively analysed and modified until all the requirements are met. The problem with such an approach is the tendency of the optimisers to exploit assumptions already 'hard-wired' in the computational models. Subsequently the design is driven towards a solution which, while promising to the optimiser, may be infeasible due to the factors not considered by the models, e.g. integration and installation of promising novel technological solutions, which result in costly design rework later in the design process.

Within this context, the aim is to develop a methodology for designing passenger aircraft families, which provides an environment for designers to interactively explore wider design space and foster innovation. To achieve this aim, a novel methodology for passenger aircraft family design is proposed where multiple aircraft family solutions are synthesised from the outset by integrating major components sets and systems architectures set. This is facilitated by integrating set theory principles and model-based design exploration methods. As more design knowledge is gained through analysis, the set of aircraft family solutions is gradually narrowed-down by discarding infeasible and inferior solutions. This is achieved through constraint analysis using iso-contours.

The evaluation has been carried out through an application case-study (of a three-member passenger aircraft family design) which was executed with both the proposed methodology and the traditional approach for comparison. The proposed methodology and the case-study (along with the comparison results) were presented to a panel of industrial experts who were asked to comment on the merits and potential challenges of the proposed methodology.

The conclusion is that the proposed methodology is expected to reduce the number of costly design changes, enabling designers to consider novel systems technologies and gain knowledge through interactive design space exploration. It was pointed out, however, that while the computational enablers behind the proposed approach are reaching a stage of maturity, allowing a multitude of concepts to be analysed rapidly and simultaneously, this still is expected to present a challenge from organisational process and resource point of view. It was agreed that by considering a set of aircraft family solutions, the proposed approach would enable the designers to delay critical decisions until more knowledge is available, which helps to mitigate risks associated with innovative systems architectures and technologies.

# Acknowledgements

I am very grateful to my supervisor, Professor Marin D. Guenov, for his guidance and patience throughout this degree, and providing me the opportunity to work with him. Without his continuous support and technical advice, this research would have not been accomplished.

I would also like to thank my past and present colleagues for their helpful suggestions and comments: Aditya Gondhalekar, Marco Nunez, Arturo Molina-Cristobal, Vis Sripawadkul, Varun Datta, Vitaly Voloshin, Xin Chen, Albert Van Heerden, and Yogesh Bile.

Finally, I would like to show my greatest appreciation to my beloved parents, wife, and son for their love and support.

# Contents

# List of Figures

# List of Tables

# Symbols

| | |
|---|---|
| $\mathrm{n_{fv}}$ | number of aircraft family variants |
| $\mathrm{C_i}$ | ith constraint |
| $\mathrm{n_c}$ | number of constraints |
| $\mathrm{V_i}$ | ith design variable set |
| $\mathrm{D_i}$ | domain of the ith design variable set |
| $\mathrm{n_v}$ | number of design variables |
| $\mathrm{V_i^+}$ | ith aggregated design variable set |
| $\mathrm{V_i^{d+}}$ | ith discretized aggregated design variable set |
| $\mathrm{p_i}$ | number of elements in the $\mathrm{V_i^{d+}}$ |
| $\mathrm{n_{mc}}$ | number of major components |
| $\mathrm{MC_j}$ | jth major component set |
| $\mathrm{q_j}$ | number of elements in the $\mathrm{MC_j}$ |
| SA | systems architectures set |
| $\mathrm{n_{sa}}$ | number of elements in the systems architectures set |
| $\mathrm{F_i}$ | ith function |
| l | number of decomposed function |
| $\mathrm{(X_j)_{F_i}}$ | jth solution for the ith function |
| $\mathrm{r_i}$ | number of solutions for the ith function |
| A | aircraft set |
| $\mathrm{n_a}$ | number of elements in the aircraft set |
| $\mathrm{A_S}$ | aircraft set for short aircraft family variant |
| $\mathrm{A_B}$ | aircraft set for baseline aircraft family variant |
| $\mathrm{A_L}$ | aircraft set for long aircraft family variant |

| | |
|---|---|
| AF | aircraft family set |
| $\mathrm{n_{af}}$ | number of elements in the aircraft family set |

*Dedicated to my family…*

# Chapter 1

# Introduction

## 1.1 Background

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 mission requirements from multiple airlines. In order to achieve this goal, civil transport aircraft manufacturing companies develop aircraft families, i.e. a group of similar aircraft which utilise common major components and systems architecture, but satisfy different performance and mission requirements. When multiple aircraft utilise common major components and systems architecture, the costs for tooling, production and assembly is reduced. Besides benefiting aircraft manufacturers, aircraft families also benefit airlines by allowing efficient route scheduling, and reducing costs for pilot cross-training through avionics and cockpit commonality. Furthermore, it reduces the spare parts inventory, which is reflected in lower maintenance costs.

Figure 1.1 shows an example of a passenger aircraft family (Airbus A320), which is comprised of four members: baseline aircraft (A320), short (A319, A318) and long (A321) variants, utilising common major components (wing and empennage) and systems architecture. Other major components (fuselage, engines, and landing gear) are exclusive among the three variants, e.g. the fuselage of the short and long variants is shrinked and stretched, respectively, to accommodate different number of passengers. Although the fuselage length, engine sea-level static

FIGURE 1.1: Airbus A320 Aircraft Family [Source: Airbus]

thrust, and landing gear mass is different for the three variants, the fuselage cross-section, engine dimensions and weight, and landing gear length are the same. In this thesis, 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, whereas the term '*system*' refers to the group of components (mostly hidden under the floor, inside wings or behind panels) that fulfil essential functions. For instance, the system realising the function "provide a 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 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) is refered to as the '*systems architecture*'.

Aircraft family design entails a significantly different approach compared to a single aircraft design: balancing multiple missions and markets, performances and costs. It involves a trade-off between 'commonality among aircraft variants' and 'performance of the individual aircraft variants', i.e. commonality leads to performance penalty of the individual aircraft variants. For instance, the weight of the individual aircraft family variants would be higher than the aircraft which was optimised separately for its own mission, but the overall life cycle cost of the whole aircraft family would be lower.

## 1.2 Motivation

### 1.2.1 Design Process and Optimisation

The conceptual design phase is of great opportunity and risks. As illustrated in Figure 1.2, it is this stage where the designer has greater freedom but relatively little knowledge about the design. As the design progresses, the knowledge about the design increases (solid-line blue curve) but design freedom is lost due to decisions made earlier (solid-line green curve). Traditional methods for designing passenger aircraft families [1] [2] [3] [4] [5] employ an optimisation-based, sequential (also known as 'synthesise, analyse, and modify') approach where a single configuration and systems architecture is selected fairly early in the conceptual design stage. The selected configuration and systems architecture are then iteratively analysed and tweaked or modified until all the requirements are met. Resolving problems due to wrong decisions made earlier incur costly design iterations (requiring new design studies to be initiated), and may lead to convergence problem specially for innovative concepts where past experience and data is unavailable. Additionally, the optimisation-based approaches have the tendency to exploit assumptions present

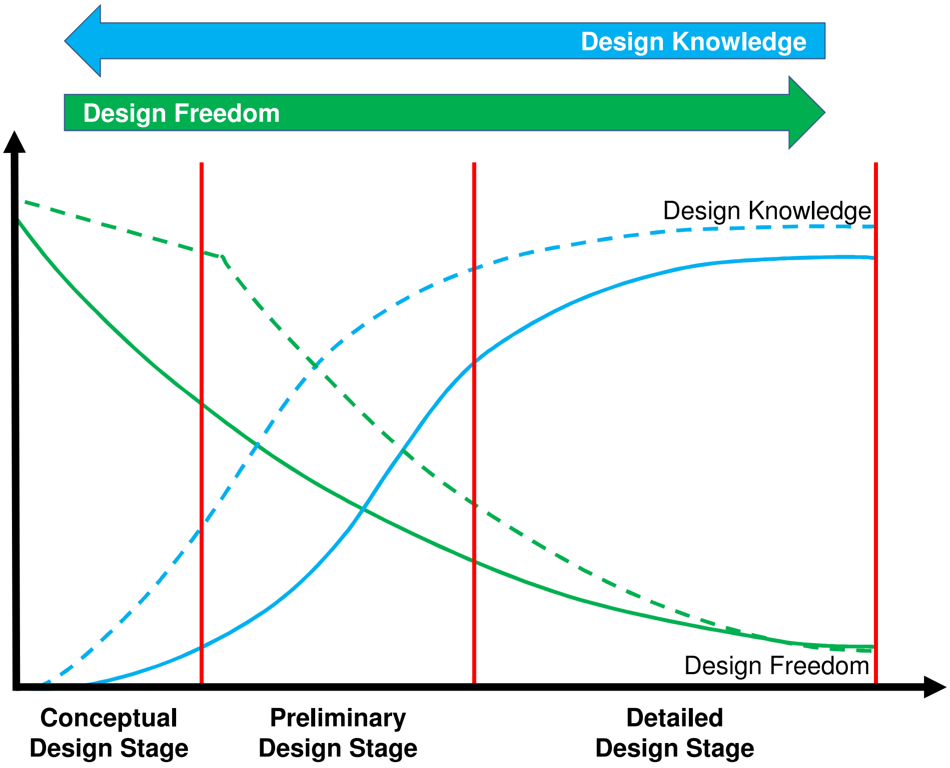


Figure 1.2: Design Freedom vs Knowledge [6]

in the computational models and to drive the design towards a solution that, while promising to the optimiser, may be infeasible due to factors not considered by the models such as integration and installation of promising novel technological solutions, which also results in costly design rework or iterations later in the design process.

Furthermore, if the design requirements change, the traditional optimisation-based approaches require the restart of 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 and requirements during the design process [6]. The changes in requirements are not only expected from customers but also how other competitors respond to market needs. For example, Boeing was originally considering to replace the third generation of 737 aircraft family with a clean-sheet design [7]. 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 [8] as customers were not prepared to wait years required for the clean-sheet design.

The ability to obtain more design knowledge early (shown by dashed blue curve in Fig. 1.2) and increased design freedom downstream (shown by dashed green curve in Fig. 1.2) in the design process would help the designer(s) to make better-informed decisions, resulting in reduced costly iterations.

### 1.2.2 Systems Architectural Design and Analysis

Aircraft systems account for roughly one-third of the total aircraft's empty weight [9] and play an important role in passenger aircraft family design where the target is to utilize common systems architecture among all the aircraft family variants. Traditionally the systems architectures are not considered during the early phase of the aircraft (family) design [10]. Statistical or empirical relations are used to estimate only systems masses as a fraction of Maximum Take-off Weight (MTOW), whereas the required power off-takes are neglected [11] [12]. Using computational models that calculate the mass of a particular sub-system as a fraction of MTOW will result in different system masses for the two variants of the aircraft family having different MTOW. If a same system architecture is employed in the two variants of an aircraft family, the computational model should give the same system mass. Therefore, a more detailed physics-based model should be used, which is based on the system's parameters. Furthermore, the effects of required power off-takes are not negligible for systems architectures analysis and technology assessment at aircraft-level.

In addition, a top-down approach is used, i.e. the aircraft configurations are frozen before moving on to the systems architecture design where the suppliers are selected and the systems architecture is defined by analysing systems' layout, interfaces and performance characteristics [10]. The systems architecture is, therefore, optimised in isolation, which results in a sub-optimal architecture 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 [13]. 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 estimates. 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.

## 1.3 Research Scope

In general, product families can be categorized into two types: module-based and scaled-based [14]. In the module-based (also referred to as configurable) product families, members of a product family are created by adding, removing or substituting functional modules, i.e. the family members provide different functionalities. In the scale-based (also referred to as parametric) families, members of a family are created by scaling (stretching or shrinking) the components, i.e. all the product family members provide the same functionalities but at the different performance levels. Module-based aircraft family design is predominantly conceived for military and Unmanned Air Vehicles (UAVs) [15] where the components are added or substituted to accomplish variety of different functions, e.g. attack/bomber, cargo, surveillance, etc. Scaled-based aircraft family design is conceived for passenger transport aircraft where major components such as fuselage are scaled to accommodate different numbers of passengers, thus satisfying different airlines' requirements in a cost effective manner. The present research focuses only on scale-based passenger aircraft family design where two Top-Level Aircraft Requirements (TLARs), number of passengers and mission range, are considered for the family creation. The number of passengers and the range for different Airbus and Boeing aircraft families are shown in Figure 1.3.

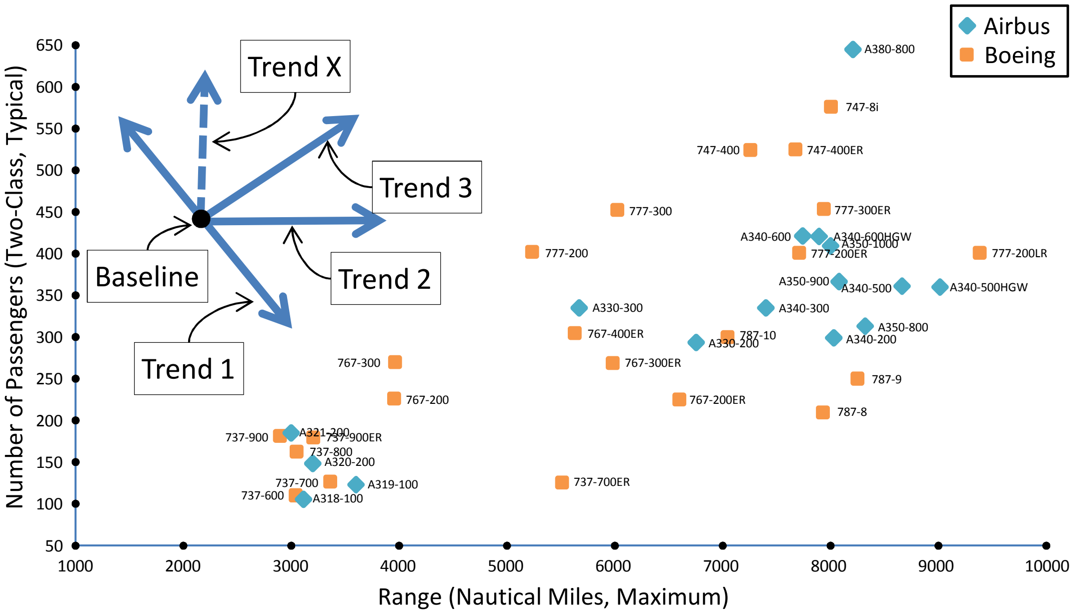


FIGURE 1.3: Civil transport aircraft family trends

It can be observed from Figure 1.3 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 total number of passengers increases, the total range decreases (e.g. Airbus A320 family). In the second trend, more fuel capacity and a higher-thrust engine, but with the same number of passengers result in Extended Range (ER) variants. For example, both Boeing 777-200 and 777-200ER have common fuselage (equal number of passengers), but the later provides longer range. In the third trend, both the number of passengers and the total range are increased by introducing higher-thrust engines and more fuel capacity (e.g. Boeing 777-200 and 777-300). As shown in Fig. 1.3, there is one trend missing (Trend X, shown by a dashed arrow), i.e. increasing the passenger capacity while keeping the similar range. For instance, currently in order to meet the high demand in Asia, large aircraft such as A340, which are optimised for long range missions, are being used for domestic (short-range) routes, resulting in poor efficiency. The present research aims to accommodate all four trends for passenger aircraft family design, whereas the creation of cargo variants [16] are not considered.

Two scaled-based approaches are used in the industry for designing passenger aircraft families: sequential and simultaneous [1]. 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 [17][18][19]. Willcox and Wakayama [1] compared the two approaches in the context of a design study of a Blended Wing Body (BWB) aircraft families. The study revealed that about 1% of the structural weight could be saved when the simultaneous approach is used. The present research accommodates both the sequential and simultaneous approaches for passenger aircraft family design.

Furthermore, the scope of the present research is restricted to the early designing of passenger transport aircraft families, which are certified according to the CS-25 [20] or FAR-25 [21] regulations.

## 1.4 Aim and Objectives

Within the above context, the aim of the current research is to develop an interactive methodology for designing passenger aircraft families that:

- Enables designers to better utilize their past knowledge, and gain knowledge about the design space (interaction between design parameters and performance metrics).
- Provides designers an environment to foster innovation by bringing more design knowledge early into the conceptual design stage.
- Is flexible to the changing design requirements.

The following objectives are set to achieve the aforementioned aim.

**Objective 1**: Investigate and identify the current trends used for designing passenger aircraft families in the industry.

**Objective 2**: Develop a formal methodology for designing passenger aircraft families at the early design stages, enabling designers to foster innovation, and interactively explore wider design spaces.

**Objective 3**: Incorporate systems architectures analysis and design earlier into aircraft family design synthesis, in order to conduct systems technologies trade-off.

## 1.5 Thesis Structure

This thesis is divided into six chapters. Chapter 1 introduces the fundamental research problem and the pressing industrial needs for designing passenger aircraft families. After providing the context, research scope and motivation for the research, the aim and objectives are outlined that guides the development of the proposed methodology. In Chapter 2, a state-of-the-art review is presented within the field of passenger aircraft family design. Furthermore, the research gaps identified from the literature review are highlighted. Chapter 2 concludes with a justification why a new methodology for aircraft family design is needed. In Chapter 3, a novel methodology for designing passenger aircraft families is presented in order to bridge the gaps identified in Chapter 2. The individual steps of the proposed methodology are explained step-by-step. In Chapter 4, the proposed methodology is demonstrated through an application case-study of passenger aircraft family design. Chapter 5 presents a critical evaluation of the proposed methodology, which is performed by means of qualitative assessment. Finally, Chapter 6 presents the findings and conclusions drawn from the current research. The limitations of the proposed methodology and the recommendations for future work are listed in Chapter 6.

# Chapter 2

# Literature Review

## 2.1 Introduction

In this chapter, a state-of-the-art review is presented within the field of aircraft family design. Furthermore, the research gaps identified from the literature review are highlighted. This chapter is divided into two main parts. In the first part, advantages and disadvantages of the different engineering design processes and methods are discussed, whereas in the second part, existing methods for designing passenger aircraft families are discussed.

In Section 2.2, the characteristics of engineering design problems, and the importance of design processes are discussed. Sections 2.3 and 2.4 present the two types of engineering design processes along with their potential benefits and disadvantages. Section 2.5 presents the systems engineering processes and the scope of the current research within systems engineering. Section 2.6 presents the phases of the aircraft design process. In Section 2.7, different engineering design methods and tools are reviewed. Section 2.8 presents the existing methods for designing product families. Section 2.9 discusses the industrial trends and existing methods for designing passenger aircraft families. Finally, Section 2.10 presents the summary and conclusions of this chapter.

## 2.2 Engineering Design

Engineering design is the creative, decision-making process of devising a product or system that meets the desired needs and requirements, where basic science, mathematics, and principles from different engineering fields are applied. The fundamental elements of the engineering design are the establishment of goals and requirements, synthesis, analysis, construction, testing and evaluation [22].

Engineering design deals with largely ill-defined and ill-structured problems. These problems are difficult to solve compared to well-defined and well-structured analysis problems. The next subsection discusses the characteristics of the engineering design problems (which make it difficult to find their solutions), and the following subsection highlights the importance of engineering design processes for solving these problems.

### 2.2.1 Engineering Design Problems

The characteristics of the engineering design problems are summarised below [23].

1. Engineering design problems have no definitive formulation. The design criteria or requirements get changed multiple times during the design phase. For complex products, such as aircraft, the design phase lasts for many months, which implies that there is a high probability of customer requirements changing. Furthermore, many design requirements emerge as a result of the design solutions evaluation. Hence, a temporary (unstable) formulation of the design problem is defined at the start of the project, which is continuously changed as more information becomes available.

2. Engineering design problems have no standard rules to obtain a solution. Most of the time, the method to obtain the solution is influenced by the way the design problem is formulated, which makes it difficult to formulate the design problem without referring to a solution. In fact, the initial proposed solutions are used as a means to understand the design problem.

3. Engineering design problems are open-ended. There are always more than one correct solutions to design problems. It is the job of the designer to find the best solution. Furthermore, the solutions to design problem are

obtained iteratively, i.e. the correct solution is rarely found the first time. Instead, the solutions are evolved and refined continually over the design phase. For instance, Wright brothers made several manned and unmanned flight attempts to come up with the first successful design.

### 2.2.2 Importance of Engineering Design Process

The solution to an engineering design problem does not suddenly appear. The characteristics of the engineering design problems (listed in the previous subsection) make it difficult for the designers to obtain a solution. In order to ease the design activity, engineering design process is employed, which is a methodical series of steps that designers follow to guide them as they solve the engineering design problems. The steps in the engineering design process specify "what should be performed", without specifying "how it should be performed". Khandani states that there are as many design processes as there are designers [24], but a good process (that enables the designers to systematically follow the series of steps) is a key to the successful design. A good engineering design process provides the designers a framework for managing the following important considerations [25].

1. Efficiency - It reduces the product design time, and eliminate the waste and expenses. It also reduces the design rework iterations, resulting from the wrong decisions made earlier.
2. Better understanding - It helps to clarify the design problem, i.e. what is needed or required. It enables the designers to utilise their past experience, and discover new ideas.
3. Innovation - It encourages to foster innovation and creativity, and prevents from selecting the first solution that comes to the mind (which may not be the best).
4. Complexity - It manages the complexity of the product, and the risks associated with different solutions. In other words, it decomposes the problem into multiple sub-problems.
5. Collaboration - It enables multiple teams to work together on a single product, which is extremely useful for complex products.

The importance of a good design process for obtaining a successful design solution is illustrated in Figure 2.1. It shows that the small portion of the cost (approximately 5%) is involved with design, whereas the remaining 95% is involved with manufacturing (materials and labour). However, the decisions made during the design process affect approximately 80% of the total cost, whereas the decisions made beyond the design phase (during manufacturing) influence only approximately 20% of the total cost. In other words, decisions made during the design process cost very little but have a major effect on the overall product cost [6]. As discussed in Chapter 1, decision are made with limited knowledge at the start of the design process. Hence, it is extremely important that the employed engineering design process enables the designers to learn and understand the design problem in order to made better-informed decision, which is one of the research objective set in Chapter 1. From the literature review, it was observed that the engineering design processes can be broadly classified into two types: iterative and convergent. The next two sections discuss the two types of design processes, and their advantages and disadvantages.

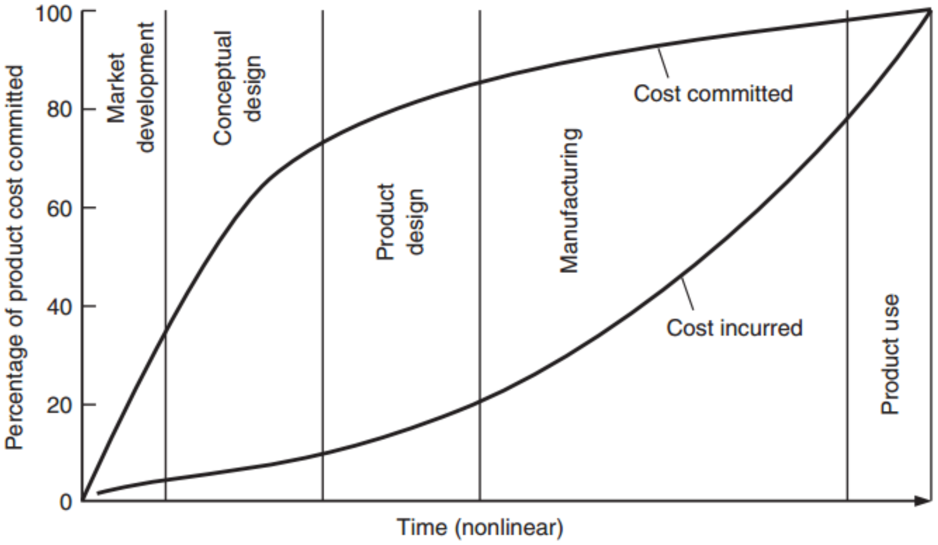


Figure 2.1: Cost Committed vs Cost Incurred [26]

## 2.3 Iterative Engineering Design Processes

Most of the time, the designers follow the approach where they propose an initial design, test it, find a problem, and then go back to the first step to make a change to the previous design. A lot of engineering design processes are developed to incorporate this iterative or cyclic nature of designing products. In these processes, a sequential "synthesise, analyse, and modify" approach is employed, where the designers select a single concept or architecture fairly early in the design process by making decisions utilizing the past experience. The selected concept or architecture is then iteratively analysed and modified until all the requirements are met. This process is also termed as Point-Based Design (PBD) process because, at any point in the design process, the designers work with only one design solution (a single point). There are many iterative engineering design processes proposed, which are suitable for designing products. Here, only two well-known design processes are discussed.

### 2.3.1 French Design Process

Figure 2.2 shows a simple stage-based design process, proposed by French [27]. The French design process is based on the design practices observed in industry.

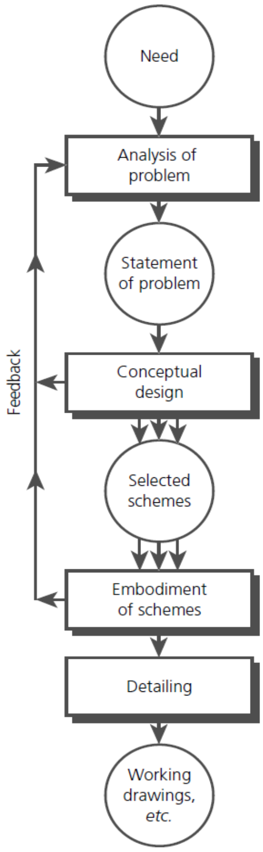


FIGURE 2.2: French Design Process, as described by Clarkson and Eckert [28]

The process is comprised of four stages, as shown in Figure 2.2. The process starts with the market survey and analysis of the stakeholder needs, which leads to the definition of problem statement. The problem statement includes the list of requirements that the product must meet. The second stage is the conceptual design phase, where multiple concepts are generated that can solve the design problem. The generated concepts are then analysed, and a single concept is chosen (which will form the basis for the final solution). The third stage is the embodiment phase, where the abstract concept is transformed into definitive layout. Finally, in the fourth stage (detailing phase), the remaining details of the design are added.

The French design process is hierarchical in nature, i.e. the project may encompass different stages of the process according to the varying completeness of each aspect of the design [28]. The French design process is very simple to follow, but it does not provide the details of the different activities in each phase.

### 2.3.2 Pahl & Beitz Design Process

One of the widely adopted version of stage-based engineering design processes was proposed by Pahl and Beitz, which is shown in Figure 2.3. The Pahl & Beitz design process [29] is comprised of four phases. Each phase consists of a list of steps (considered as useful guidelines for the design activity) which enables the designers to ensure that nothing important is overlooked. In the first phase, the design problem is analysed, and a design specification is drawn. The specification defines the functions that the product must perform, and the constraints placed on the design solution. In the second phase (conceptual design), multiple solutions are generated and evaluated. The conceptual phase starts by determining the functions to be fulfilled by the products. Next, solution principles are generated for the functions. In the third phase (embodiment design), the chosen design concept is elaborated into a definitive design. In this phase, the layout and assembly of the components and parts, and their interfaces are defined. In the final phase (detailed design), the dimensions, geometrical shapes, and materials are specified. The instructions for production, assembly, and operations are also specified in the detailed design phase.

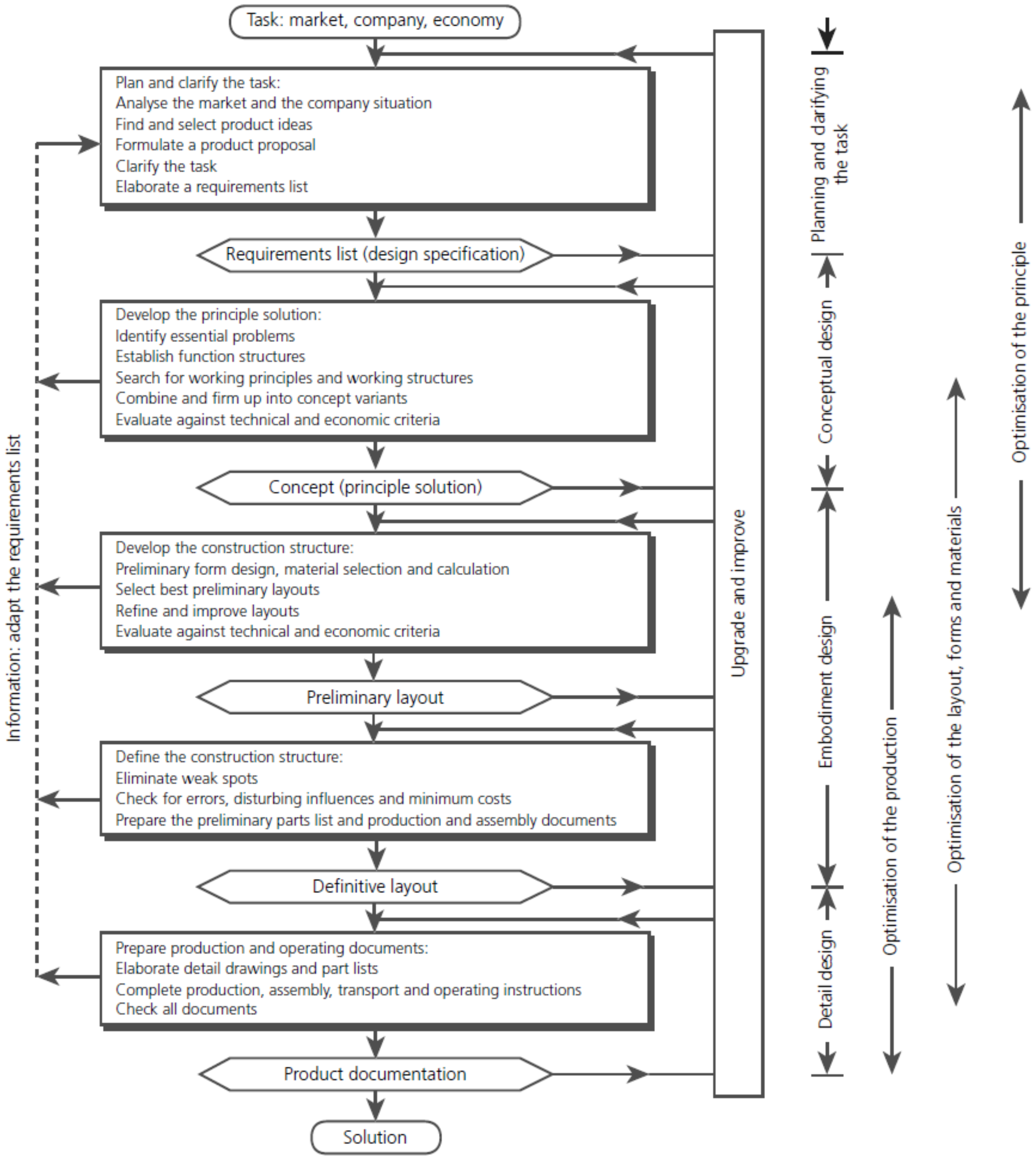


FIGURE 2.3: Pahl & Beitz Design Process [29]

### 2.3.3 Discussion of Iterative Engineering Design Processes

Although only two stage-based engineering design processes are described here, there are many processes proposed, e.g. Pugh [30], Roozenburg & Cross [31], Ullman [6], Hubka [32], etc. However, Roozenburg and Eekels state that most of the processes converge to a four-phase design process [33]. The details about the other engineering design processes can be found in references [34] [35]. More recently, researchers have tried to incorporate creativity in these design processes [36].

One of the limitations associated with the stage-based design processes is that the sharp division between the phases cannot be drawn [33]. Furthermore, these stage-based design processes assume that the design proceed from the abstract to the more concrete definition, therefore too much attention is paid to the conceptual phase, at the expense of embodiment and detailed design phases [33].

Another limitation associated with these simple design processes is that these processes do not consider other disciplines or phases such as manufacturing, assembly, production, sales, operations, maintenance, disposal, etc. In order to overcome these limitations, concurrent engineering [37] method was developed, which led to the development of Integrated Product Development (IPD) process. The concurrent engineering is a method of designing and developing products, where different disciplines or phases run simultaneously (rather than consecutively). It decreases the overall product development time, improves the productivity, reduces costs, and brings the product to market earlier. The most important benefit of the concurrent engineering is that it reduces the number of design changes (resulting from the wrong decisions made earlier), as shown in Figure 2.4.

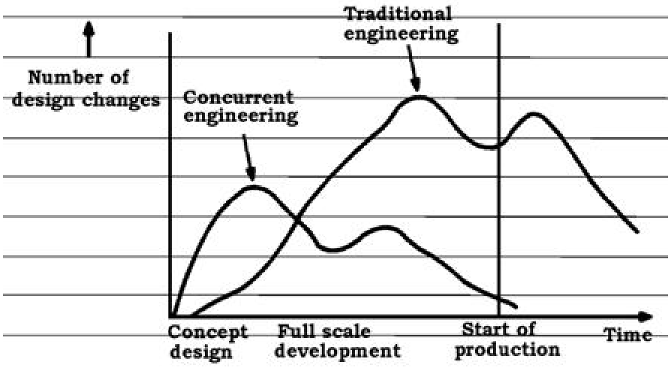


FIGURE 2.4: Design Changes Reduction in Concurrent Engineering [38]

## 2.4 Convergent Design Processes

After discussing the iterative design processes, this section presents the convergent design processes. In convergent design processes, the emphasis is on the synthesis and analysis of multiple design solutions. As the design progresses, more design knowledge is gained and infeasible or inferior design solutions are eliminated. Keeping the design space open longer enables the designers to gain a better understanding of the design and the requirements that it is supposed to meet. Three different convergent design processes are described in this section: design-build-test, total design, and set-based design.

### 2.4.1 Design-Build-Test Process

Wheelwright and Clark proposed a design method based upon the design-build-test cycle [39], as illustrated in Figure 2.5.

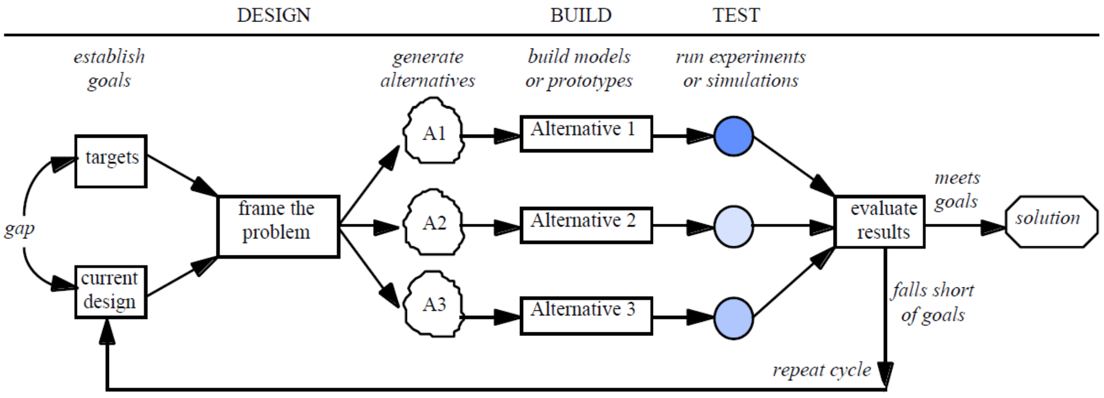


Figure 2.5: Design-Build-Test Method [40]

In the first step, product and manufacturing process requirements are established by clarifying the stakeholder needs. In the second step, several design solutions are synthesised. The goal of considering the multiple solutions is to explore the relationships between design and performance parameters. The computational models or prototypes are then constructed to evaluate the performance parameters. In the third step, the synthesised solutions are assessed against the product requirements. If a solution satisfies all the requirements, the process stops, otherwise the design-build-test cycle is repeated again, until all the requirements are met. A single design-build-test cycle is used to provide information to the next cycle. The effectiveness of this method depends upon the number of cycles that are completed and how well the results of individual cycles are combined into coherent solutions [39].

### 2.4.2 Total Design (Controlled Convergence) Process

Pugh proposed a method, called Total Design (also known as controlled convergence) [30], as illustrated in Figure 2.6.

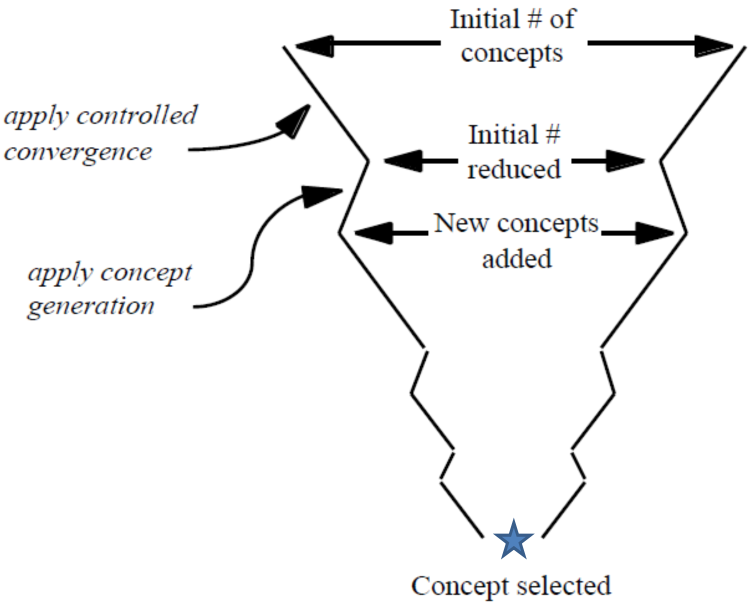


Figure 2.6: Total Design (Controlled Convergence) Method [40]

This method is a repetitive two-step process. In the first step, designers synthesise a large number of design solutions. In the second step, these solutions are evaluated and assessed against the customer's requirements. The solutions which are better in performance are retained, while the others are discarded. After the first reduction of the solutions, the designers synthesise additional design solutions (either through modifications of the initial solutions or entirely new solutions). The set of solutions (old and new) is narrowed further by discarding weaker solutions. This process continues in this fashion, with the generation of solutions followed by the reduction of solutions. Each successive repetition of the generation and reduction process results in narrower set of solutions, until only one design solution remains. This repetitive expansion and contraction process is illustrated in Figure 2.6.

### 2.4.3 Set-Based Design (SBD) Process

The Set-Based Design (SBD) method was developed by Toyota automotive company [41] [20]. In SBD, the designers consider a wider range of design solutions from the outset, and then explicitly communicate and reason about the solutions by evaluating the performances parameters, and then gradually reduce the set by eliminating infeasible and inferior solutions that do not meet the performance requirements (until a final solution remains). Figure 2.7 illustrates the concept of SBD.

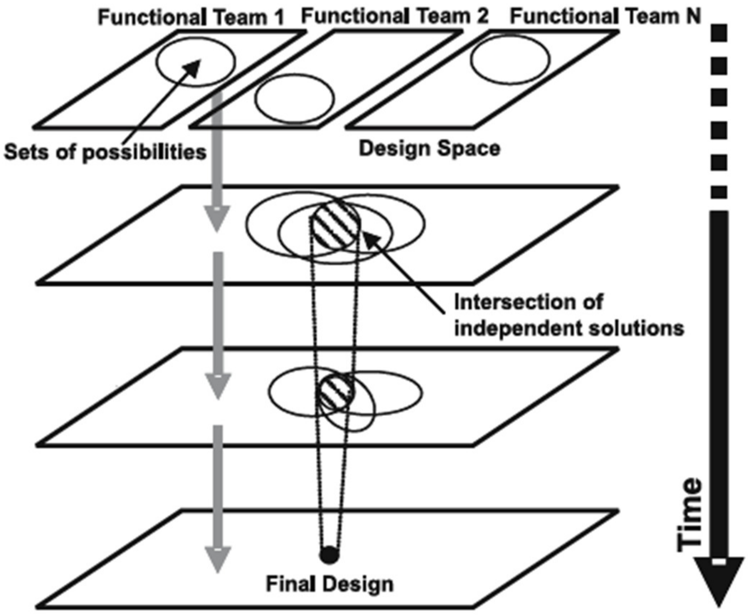


FIGURE 2.7: Set-Based Design Method [42]

Sobek *et al.* describe the three main principles of SBD:

1. Map the design space - achieve a thorough understanding of the set of design possibilities, also known as the design space;
2. Integrate by intersection - ensure that design teams integrate sub-systems by identifying solutions that are workable for all functional groups; and
3. Establish feasibility before commitment - narrow sets down to an optimum solution at the system level.

SBD has the advantage of not locking up at a specific design solution too early, since a lot can happen during the design stage that can change the requirements [43] [44]. Furthermore, the design rework that occurs late in the design process is exponentially more expensive than design work performed early in the cycle [45]. Nahm and Ishikawa proposed a set-based design methodology which integrates meta-modelling techniques, fuzzy set theory, design of experiments, and robust analysis techniques [46] [42]. Inoue *et al.* proposed a set-based design approach that obtains a ranged set of feasible solutions while incorporating the designer's preference for design parameters [47]. US Navy has also utilised SBD approach during the preliminary design of Ship to Shore Connector program [48]. Considering multiple solutions earlier and delaying certain decisions seems counter intuitive, but it's purpose is to prevent from getting rid of good ideas, and reducing the development risks and design rework or iterations [49]. The risk reduction in SBD occurs due to redundancy, knowledge gain, and robustness [50] [45]. Although considering multiple solution helps to reduce risks (specially associated with the innovative design solutions), Sobek *et al.* indicate that it requires a lot of people and resources for synthesis and analysis [20], i.e. right amount of design solutions should be considered that add value to the product without causing cost increase. Rocha *et al.* performed a study which indicates that even though the use of multiple concepts can be advantageous, the decision about quantity of concept developed simultaneously affects the potential development gains. Rocha *et al.* conclude that the SBD provides great development advantages when used in mid-high complexity projects. Simple follow-on or evolutionary products may better use traditional or iterative one-hit (point-based) design practice, since an elevated amount of workload to develop multiple concepts would impact negatively on the overall development performance.

### 2.4.4 Discussion of Convergent Engineering Design Process

Convergent engineering design processes consider a wider range of design solutions from the outset. The designers then reason about the design solutions by evaluating the performances parameters. Finally, the set of design solutions is gradually reduced by eliminating infeasible and inferior solutions that do not meet the requirements, until a final solution remains. Convergent engineering design processes enable the designers to make better informed decisions by delaying the critical decisions, as more knowledge is gained. In other words, it encourages the designers to foster innovation by preventing them from immediately elaborating on the first concept or architecture that comes into mind, which may not be the best. Furthermore, these processes do not require fixed requirements. Instead, the evolving requirements are accommodated, without requiring extra design rework for the changing requirements.

## 2.5 Systems Engineering (SE)

Relatively simple products can be designed with a small number of designers and engineers. However, as the complexity of the products increases, the number of interactions between many components also increases. The complexity is not only related to the engineering aspects of the products, but also to the management and organization of the designers and engineering from different disciplines, large amount of data and many decisions. The increased product complexity arose the need for systems engineering (SE). In SE, the complex product is decomposed into many systems, systems into many subsystems, and subsystems into many components. This division or decomposition enables easy management of the work involved in each system design while ensuring that the overall product meets all of the functional requirements. SE enables the systems engineers to manage the interfaces between various systems, subsystems, and components, which requires understanding of the different types of interfaces such as physical connection, energy transformations, fluid flow, etc. In order to implement the systems engineering for designing complex products, different systems engineering processes have been proposed. In this section, some of the widely known systems engineering processes are discussed.

### 2.5.1 Department of Defence (DoD) SE Process

The Department of Defence (DoD) SE process [51] is a widely accepted SE process. As shown in Figure 2.8, it captures all the principles of SE, i.e. decomposition, definition, integration, and verification. The DoD systems engineering process is a top-down iterative and recursive problem-solving process, which is applied through all the development stages. In DoD process, two types of architectures are developed, i.e functional and physical, which describe different aspects of the system under development. The functional architecture embodies the structure of the allocated functional requirements, whereas the physical architecture provides the breakdown structure of the physical system into multiple subsystems, components, and parts.

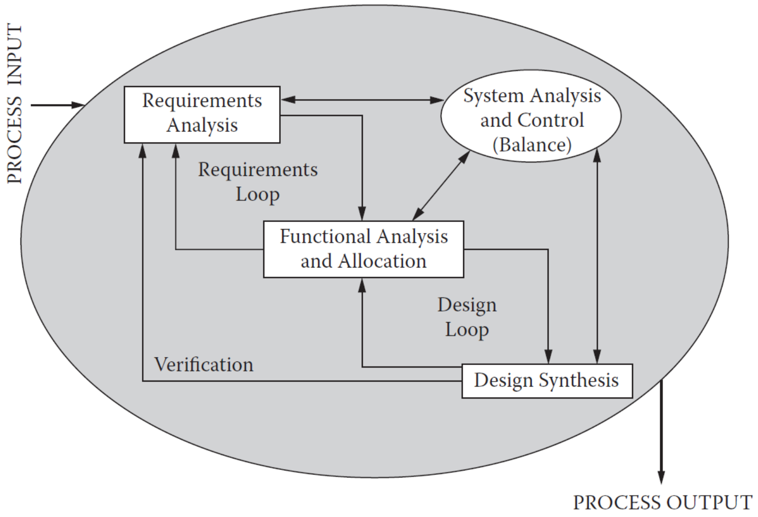


FIGURE 2.8: Department of Defence (DoD) Systems Engineering Process [51]

The major tasks of the DoD systems engineering process are listed below. All of these tasks are performed in each iteration as more design issues and product details are considered at a lower level.

1. Requirements analysis, i.e defining and documenting the requirements for tracing and verification.
2. Functional analysis and allocation, i.e. (1) identification of all the functions of the product (including its systems, subsystems, and components) and (2) assigning functions to each system, subsystem, and component of the product.
3. Design synthesis, i.e. generating partial solutions and then integrating the partial solutions into the whole product.
4. Evaluation, i.e. considering the trade-off between requirements (performance, safety, quality, costs, and timing schedules).

Figure 2.9 presents a more detailed description of the DoD systems engineering process. The red dashed-rectangle represents the scope of the current research with in systems engineering process, which involves the application of the functional analysis results to the design of product such that the entire product with interfaces between various systems, subsystems, and components can perform to meet all the requirements. In particular, the current research focuses on two aspects of the systems engineering:

1. Synthesis of the aircraft family solutions (at aircraft major components and systems level) by using the results of the functional analysis and allocation.
2. Refinement and down-selection of aircraft family solutions through analysis and requirements or constraints satisfaction.

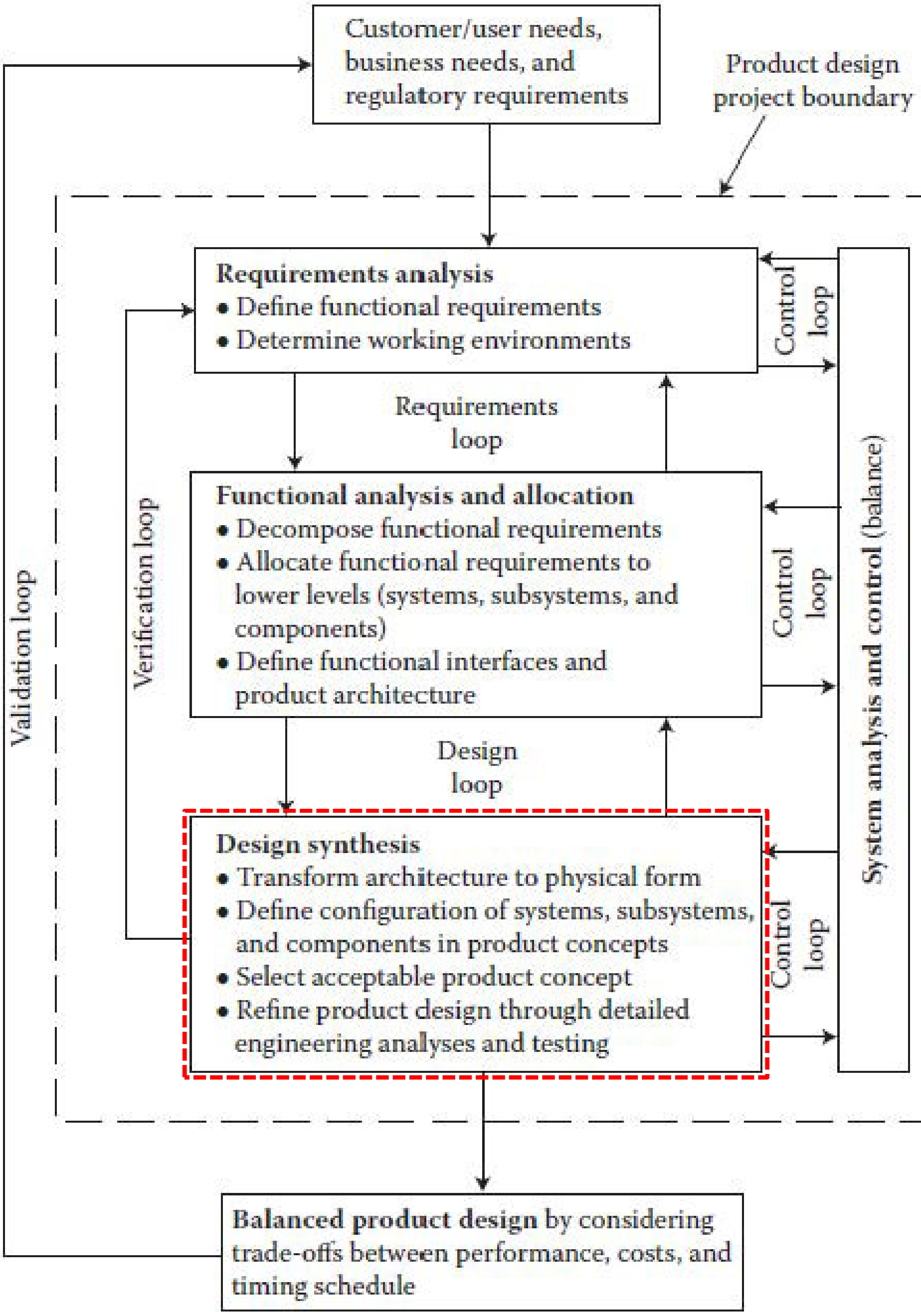


FIGURE 2.9: Detailed Description of the DoD Systems Engineering Process [52]

Other aspects such as requirements analysis, and functional analysis and allocation are not the focus of this research. Furthermore, management of the organisations and resources such as people, time, etc. are also not considered in this research. The practices and tools addressing these aspects are addressed in various systems engineering standards [53] [54] [55] [56].

### 2.5.2 Vee SE Process

One of the most widely used systems engineering process is the V (pronounced as vee) process [57], as shown in Figure 2.10. In the V SE process, the sequence of the steps starts from the top-left (by specifying the system's requirements) and finishes at the top-right (by validating the system's requirements), i.e. the system's maturity increases from the left to right. Overall, the vee SE process is divided into two parts. The left part (downward-steps) deals with the synthesis (decomposition and definition) of the system. The right part (upward steps) deals with the integration (testing, assembly, and verification) of the subsystems. As the integration and verification at the right part of the vee SE process is dependant on the development of system's specification at the corresponding right part, therefore there is a direct correspondence between steps of the left and right parts, as shown in Figure 2.10.

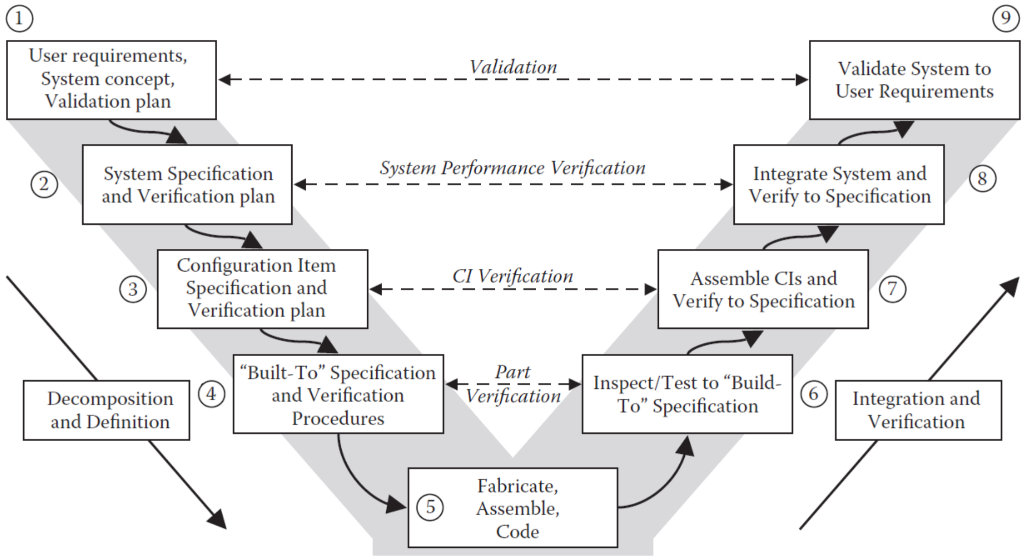


FIGURE 2.10: V Systems Engineering Process, as described by Dickerson and Mavris [58]

### 2.5.3 Waterfall SE Process

The waterfall systems engineering process [59] is a sequential process with a series of steps, which originated in the software engineering. Figure 2.11 shows the steps of the waterfall systems engineering process. Here, the design flows down to the subsequent steps once the current step is completed. Royce states that as the design is progressed at each step of the process (by increasing the details), there is an interaction with the previous and the next steps but rarely with the very remote steps [59]. Figure 2.11 shows this interaction between the consecutive steps. This corresponds to the iterative nature of the design activity.

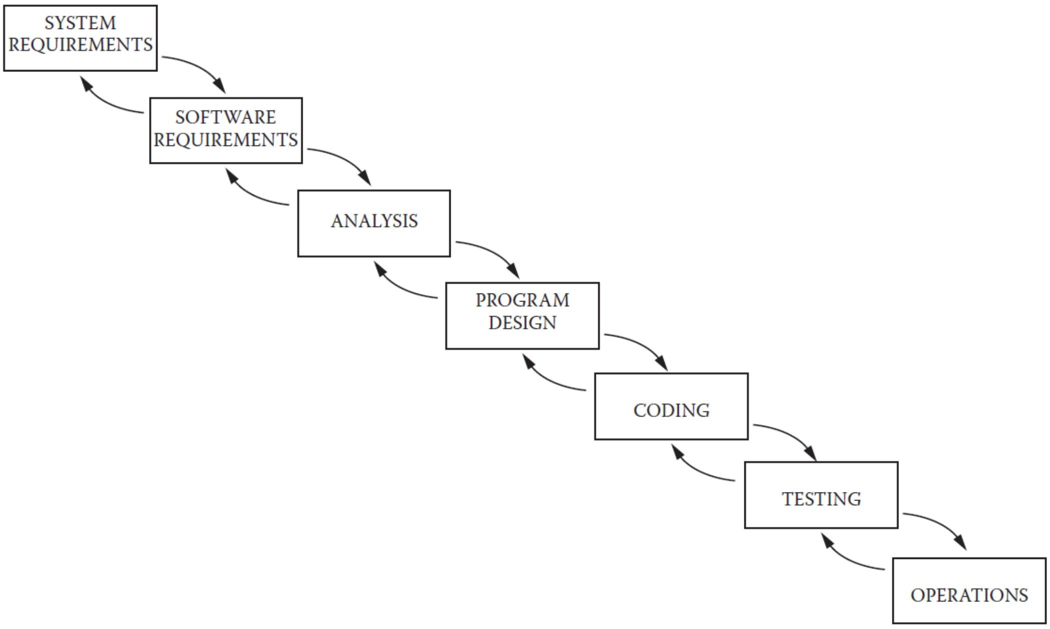


Figure 2.11: Waterfall Systems Engineering Process, as described by Dickerson and Mavris [58]

### 2.5.4 Spiral SE Process

The spiral systems engineering (SE) process [60] was also originated from the software engineering for developing large-scale software. Figure 2.12 shows the spiral SE process. The spiral systems engineering process has two distinguishing features. The first is the iterative approach for incrementally increasing the systems degree of definition, i.e. the system is defined at a more detailed level with each loop of the spiral, whereas the second feature is the presence of multiple milestones in order to ensure that the system meets the stakeholder requirements [60]. Each loop of the spiral is composed of the multiple phases [10]: (1) determining objectives, constraints, and then gererating alternatives (2) evaluating alternatives and risks; (3) developing, verifying, and redefining the product; (4) planning for the next loop. The output of each loop becomes the input of the next loop.

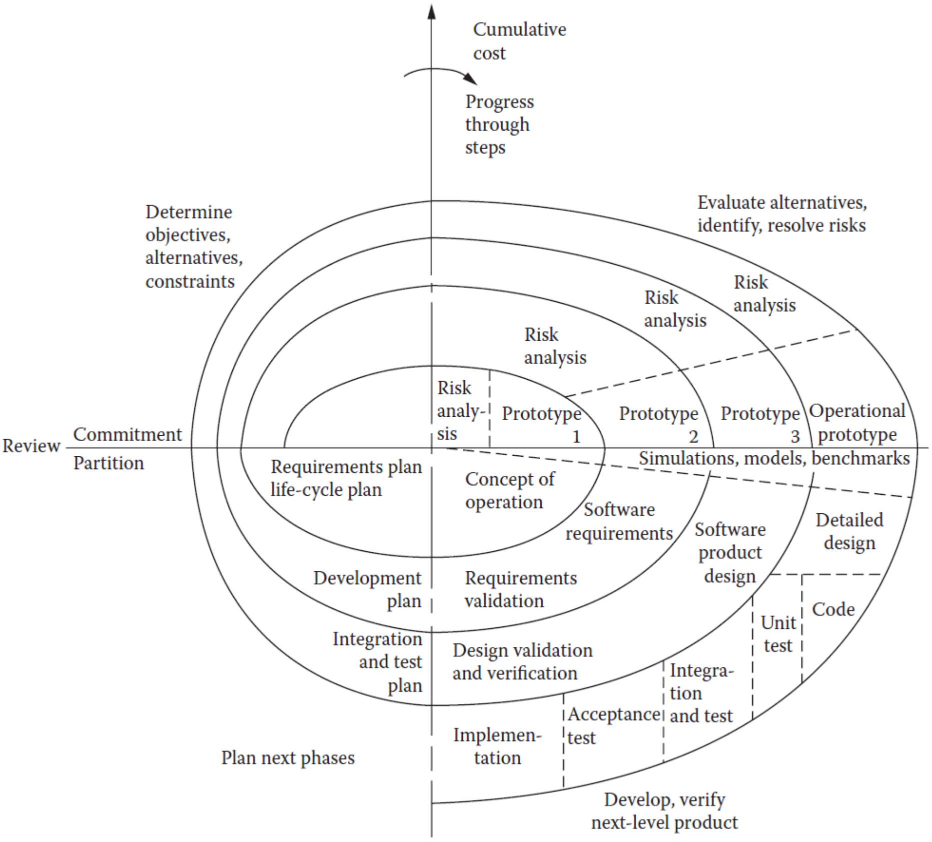


FIGURE 2.12: Spiral Systems Engineering Process, as described by Dickerson and Mavris [58]

### 2.5.5 Discussion of Systems Engineering Processes

In this section, widely used systems engineering processes were described, which consider all the stages (designing, manufacturing, production, assembly, operations, maintenance, and disposal) of the product life-cycle. These processes enable the designers to manage the product complexity by providing useful guidelines. However, these processes employ iterative "synthesise, analyse, and modify" approach, which results in the costly design changes at the later stages of the product development (especially for innovative concepts).

## 2.6 Aircraft Design Process

The aircraft design process is usually divided into three phases [11] [61] [62] [12]: conceptual design, preliminary design, and detailed design. The conceptual design phase deals with the selection of best aircraft configuration. Here, the basic question to be answered is "what should be the configuration arrangement?", i.e. determining the overall geometry of the wing and tail, the fuselage shape, the number of engines and their locations, etc. Furthermore, the rough estimates of the sizes, weights, and performances are determined. Raymer states that the conceptual design phase is very fluid [11], i.e the configuration and layout of the aircraft is always being changed (due to the new information and knowledge obtained about the design). The changes can be introduced in any aspect of the design, e.g. wing configuration, tail arrangement, number of engines, propulsion type, etc. The preliminary design phase starts when the major decisions have been taken, e.g will canard configuration be used?, what will be the propulsion type?, how many number of engines?, what will be the wing and tail configuration?, etc. In preliminary design phase, the major tasks are to freeze the aircraft configuration, develop lofting (surface definition), and design structural components and systems. At some point in the preliminary design phase, the overall design is frozen (when the company believes that it has sufficient information). This allows the other designers to begin detailed analysis of the major structural components and systems architectures without fearing that their work will be invalidated by the later changes to the overall design configuration. The detailed design (also called the full-scale development) phase is characterised by a large number of designers preparing detailed drawings or computer-aided design (CAD) models, and analysis with high-fidelity computational tools or experimental tests. Furthermore, thousands of small parts which are not considered during the preliminary design phase, e.g. doors, flap tracks, and avionics racks, are designed during the detailed design phase. Another important task at the detailed design phase is the "consideration of how will the aircraft components and systems be fabricated?".

Figure 2.13 shows the phases of the aircraft design process. As shown in Figure 2.13, Kundo adds another (fourth) phase (fabrication phase), which deals with the aircraft assembly, flight testing, etc.

It can be observed from the previous discussion that the traditional process for designing aircraft is a point-based approach, where the designers look for quickly

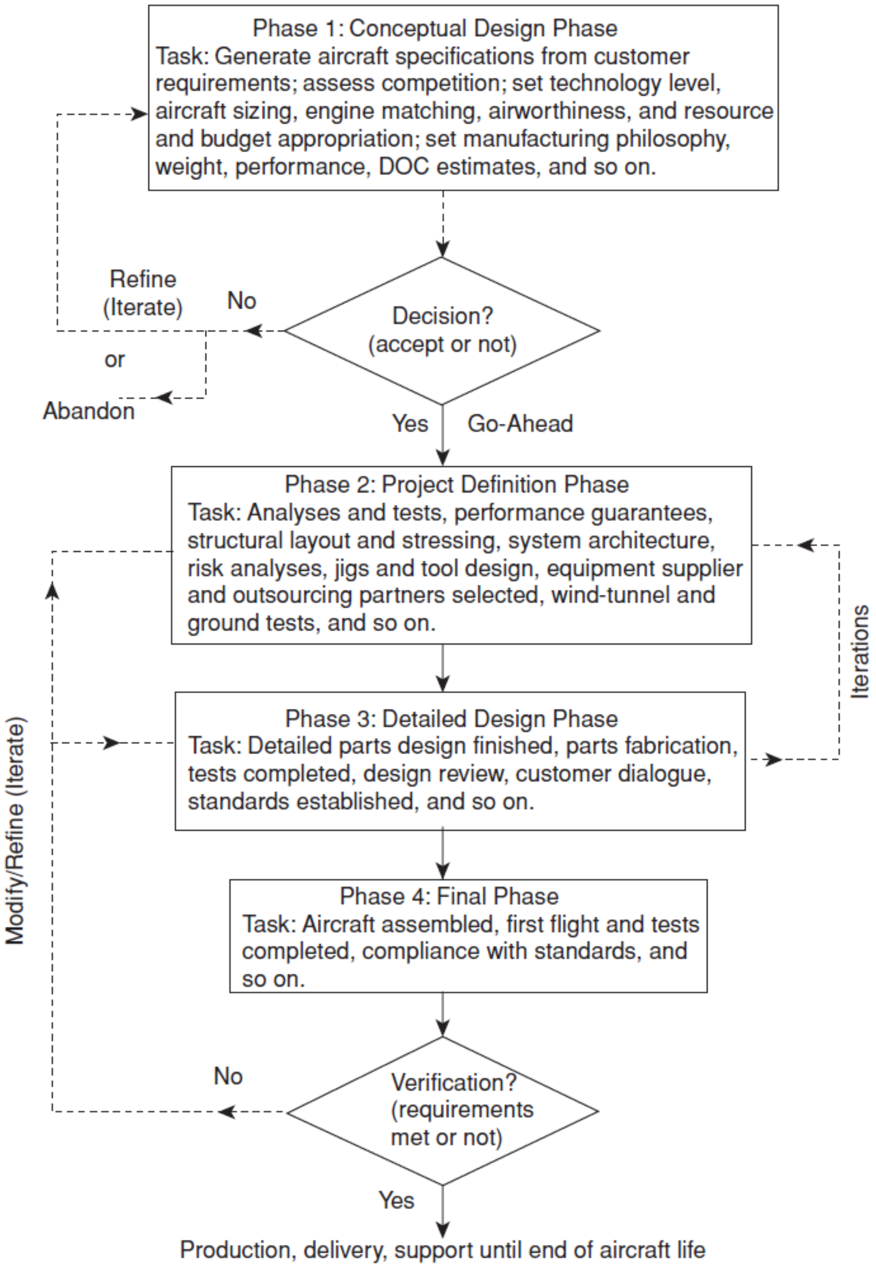


FIGURE 2.13: Aircraft Design and Development Process [63]

selecting or locking the configuration and systems architecture. After the concept and systems architecture is frozen, the next task is to iteratively modify the selected concept and systems architecture (while increasing the design details), until all the requirements are met. Two major problems are associated with the traditional (point-based) aircraft design process.

The first major problem is that if the design requirements change, it requires the restart of the whole process all over again, resulting in costly design rework. The aircraft design process is very complex which takes many months, as shown in

Figure 2.14, which implies that there is a high probability of customer requirements being changed. Furthermore, many problems (e.g. integration issues) appear late in the design process which makes the tradition point-based aircraft design process ineffective (due to the extra studies for handling design changes).

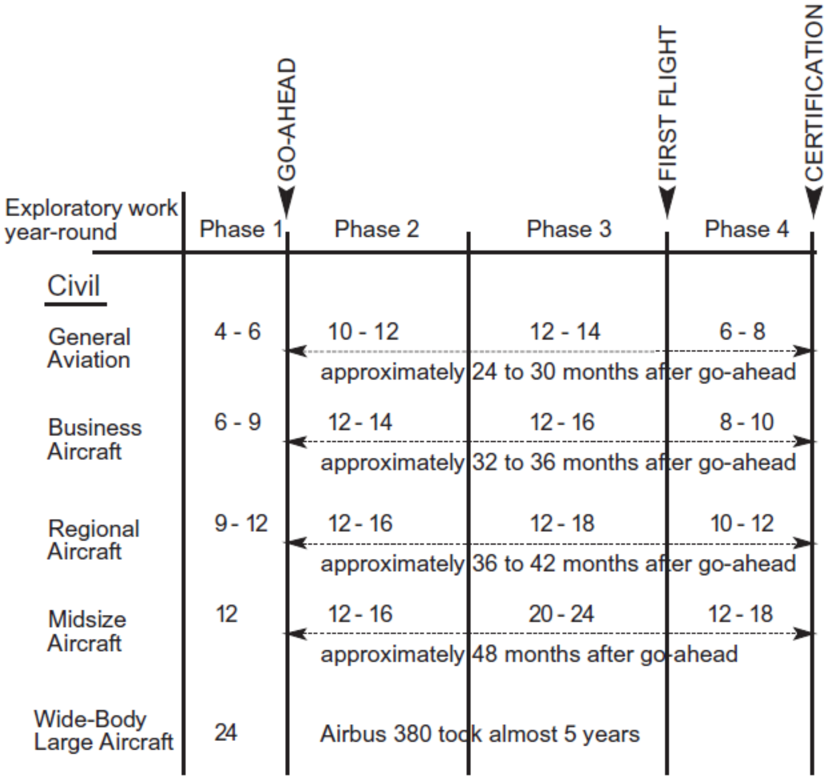


Figure 2.14: Typical Aircraft Design Process Time Frame (in months) [63]

The other major problem is that systems architectures analysis and design is considered very late in the design process. The aircraft configurations are frozen before moving on to the systems architecture design where the suppliers are selected and the systems architecture is defined by analysing systems' layout, interfaces and performance characteristics [10]. The systems architecture is, therefore, optimised in isolation which results in sub-optimal architecture with under or over-estimated performances due to overlooked interactions between systems and their impact on the whole aircraft.

## 2.7 Analytical Design Methods and Tools

This section presents a list of analytical design methods and tools: axiomatic design, theory of inventive problem solving (TRIZ), house of quality (HoQ) matrix in quality function deployment, and multidisciplinary design optimisation (MDO).

### 2.7.1 Axiomatic Design

Axiomatic design [64] [65] [66], developed by Suh, focuses on mapping the relationships in a design. Axiomatic design "is about how to think and use fundamental principles during synthesis or mapping between the domains of the design world" [64]. The four domains are the customer, functional, physical, and process. Interrelations between these domains are represented by a design matrix, and are determined using a form of transfer function, also known as mapping. The domain structure and mapping relations are shown in Figure 2.15. Moving from left to right, the mapping represents the transition from what is desired to how it can be achieved.

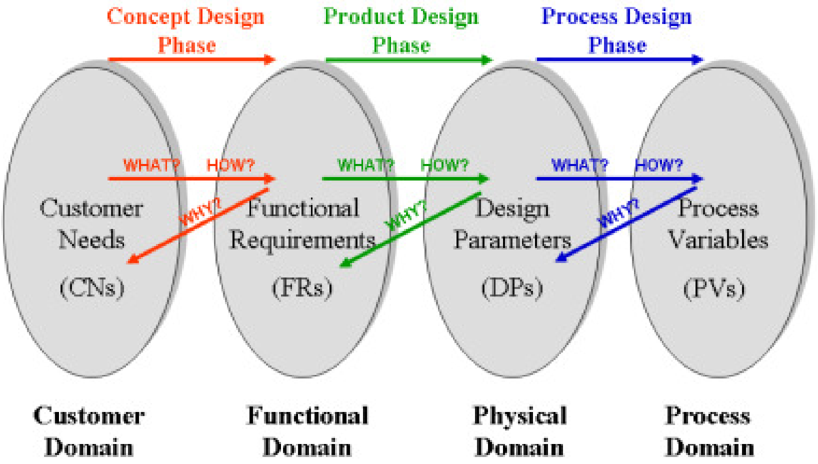


FIGURE 2.15: Axiomatic Design Method [66]

Suh states that there are two fundamental axioms to govern the design process [64] [66]:

- Axiom 1: The Independence Axiom Maintain the independence of the functional requirements.
- Axiom 2: The Information Axiom Minimize the information content.

Axiom 1 states that during the mapping process, functional requirements that the design must meet are independent, which translates into a design matrix that is either diagonal or triangular. Axiom 2 defines information content as the probability of satisfying a given functional requirement. Higher probabilities of success are preferred designs. Within each domain, there are hierarchies that represent the design decomposition. Mappings can occur between any hierarchy levels across the domains. The stated advantage of this formulation is that designers are encouraged to consider innovative design solutions.

Axiomatic design has been proposed in many fields and applications, but has recently lost support due to the difficulty of describing a practical design in its axiom and domain formulation [67].

### 2.7.2 Theory of Inventive Problem Solving (TRIZ)

TRIZ [68] [69] is a concept generation method, where innovative and creative solutions are developed by using the condensed knowledge of past inventors. TRIZ is the Russian acronym for the theory of inventive problem solving. It was originated from the extensive studies of the technical patents. Altshuller (the founder of TRIZ) studied a collection of patents and observed that only 1% of the presented solutions were truly pioneering inventions, whereas the rest of the presented solutions represented the use of previously known ideas and concepts but in a novel way [2]. He concluded that the solution to a new design problem might already be known. Figure 2.16 shows the basic structure of the TRIZ [70].

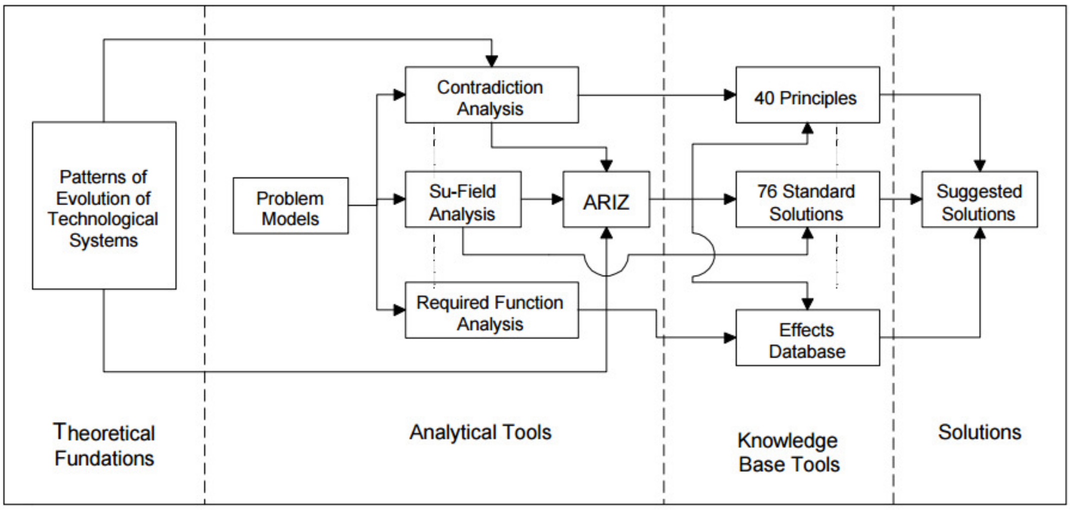


FIGURE 2.16: TRIZ (Theory of Inventive Problem Solving) Structure [70]

As shown in Figure 2.16, there are two types of tools used: analytical and knowledge base. The analytical tools include contradiction analysis, Substance field analysis, required function analysis, and ARIZ (Algorithm for Inventive Problem Solving). These analytical tools generalize a specific situation to represent a problem as either a contradiction, or a substance-field model, or just as a required function realization [70]. ARIZ is such a sophisticated analytical tool that it integrates above three tools and other techniques. The knowledge base tools include 40 inventive principles. 76 standard solutions, and effects of knowledge base. These tools are developed based on the accumulated human innovation experience and the vast patent collection. The knowledge base tools are different from analytical tools in that they suggest ways for transforming the system, while analytical tools help changing the problem statement in favour of problem solving [70]. The details of the TRIZ tools can be found in the references [68] [69].

Like axiomatic design, it is very difficult to implement TRIZ in the industrial setting. However, researchers have tried to combine these methods, which enhances the early conceptual design. For instance, uncoupling the design matrices of axiomatic design by recasting the coupled functional requirements as technical or physical contradictions in TRIZ [71].

### 2.7.3 House of Quality (HoQ)

Quality Function Deployment (QFD) was originated in Japan during 1960s as a quality improvement process. At the heart of the QFD process is the House of Quality (HoQ) tool [72], consisting of several matrices, which is generally used to translate the stakeholder' needs (specified as 'whats') into engineering characteristics (specified as 'hows'). HoQ helps to meet or influence the stakeholder' needs, aka voice of the customers (VOC), which leads to increased customer satisfaction [72].

The structure of the HoQ is shown in Figure 2.17. The stakeholder needs are identified and listed hierarchically in section (a). The stakeholder needs are then assigned priorities by communicating with customers, which are listed in section (b). The performance of the competitors may also be assessed against stakeholder needs, which is listed in section (c). Next, the technical characteristics (measurable requirements) are specified in section (d). These measurable requirements are the performance constraints, and are identified by multidisciplinary teams. After listing the stakeholder needs and the engineering characteristics, the relationship matrix is created in section (e). The relationship matrix specifies which engineering characteristics impact the stakeholder needs, where the relations (represented by symbols) can be weak, strong, positive, or negative. Next, the relationships among engineering characteristics are specified in section (f), sometimes known as the roof-matrix. In the end, the target values of the engineering characteristics are specified in section (g) which may also include other information such as the difficulty level in achieving those target values. Finally, the weighted importance of the engineering characteristics is listed in section (h).

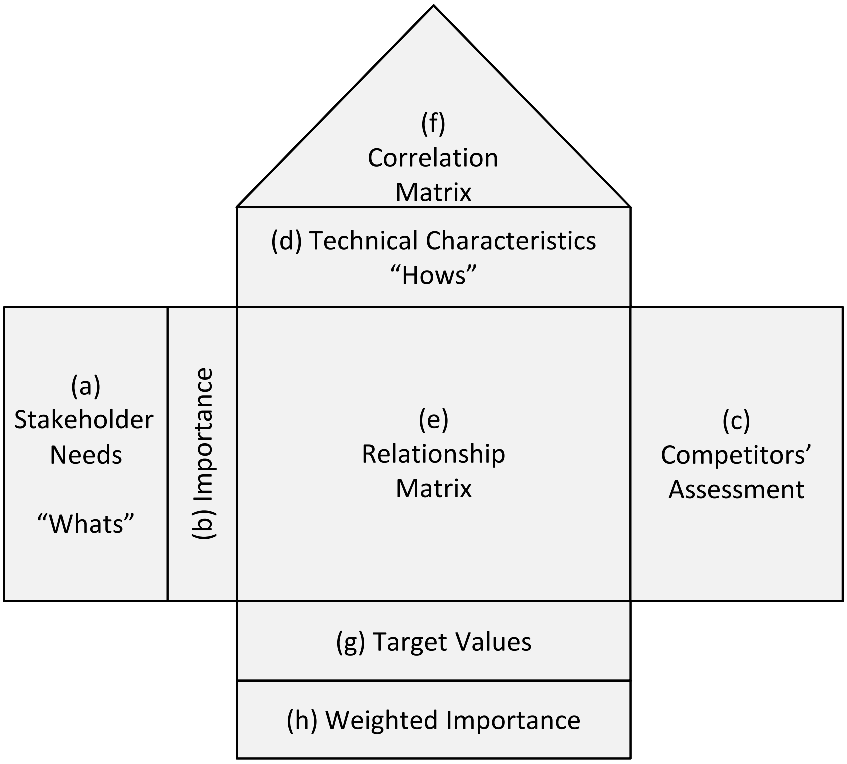


Figure 2.17: House of Quality (HoQ) Structure

### 2.7.4 Multidisciplinary Design Optimisation

Optimisation is the use of mathematical models to analyse and compare alternatives to identify an "optimal" or best alternative. Multi-disciplinary design optimisation (MDO) combines optimisation techniques with computational models to trade-off aspects of a design to achieve an "optimal" solution, not just a feasible one. The MDO field is extensive and spans many disciplines. Martins and Lambe [73] and de Wit and van Keulen [74] provide overviews of the MDO architectures and strategies. Section 2.9 describes in detail some of the MDO architectures used for designing passenger aircraft families.

While useful, it is important to understand the limitations of MDO. It has the tendency to exploit assumptions present in the computational models and to drive the design towards a solution which, while promising to the optimiser, may be infeasible due to factors not considered by the models such as integration and installation of promising novel technological solutions. This results in costly design rework or iterations later in the design process. In addition, a criterion for evaluating alternatives (i.e. MDO formulation) and choosing the best solution cannot be unique [75]. Its choice will be influenced by many factors such as the design application, timing, point of view, and judgement of the designer, as well as the individual's position in the hierarchy of the organization. If the computational models and optimisation techniques could be used to design artefacts, then it is fair to say that human designers would not be required for complex systems design. MDO is a valuable tool that aid designers in the decision making process. However, the results from applying these tools should be tempered with an understanding of how the models were developed and what is the range of inputs the model is applicable. Furthermore, if the design requirements change, the new MDO formulation is required, hence restarting the whole process of MDO all over again.

## 2.8 Product Family Design

After describing the engineering design processes and methods, this section presents the state-of-the-art in the field of product family design. First, the two different categories of product families are described, then a list of product family design methods, found in literature, are presented.

### 2.8.1 Product Family Types

Product families can be categorized into two types: module-based and scaled-based [14]. In the module-based (also referred to as configurable) product families, members of a product family are created by adding, removing or substituting functional modules, i.e. the family members provide different functionalities. In the scale-based (also referred to as parametric) families, members of a product family are created by scaling (stretching or shrinking) the components, i.e. all the product family members provide the same functionalities but at the different performance levels.

### 2.8.2 Product Family Design Methods

Two approaches can be used for designing product families: top-down and bottom-up [14]. In the top-down approach, the company strategically develops a product family based on the stakeholder needs. In the bottom-up approach, the company redesigns or consolidates a group of already existing distinct products by standardising the components.

Simpson *et al.* proposed a method for product family design, named Product Platform Concept Exploration Method (PPCEM) [76] [77] [78], which is comprised of five steps. In the first step, the design requirements are mapped to market segments [79]. In the second step, the design requirements and the market segmentation grid are mapped to the design factors and their ranges are determined. After determining the design factors and their ranges, common and scalable design factors are identified. In the third step, meta-models (surrogate models) are built for computationally expensive analysis models. In the fourth step, the values of the common design factors are determined using compromise Decision Support Problem (cDSP). The cDSP is a multi-objective decision model [80] which is used to determine the design variables values in order to achieve a collection of goals while satisfying a collection of constraints. The overall objective is to minimize the deviations of goals from the target values using lexicographic minimization [81]. Finally, in the fifth step, customised product family variants are developed by determining the values of scalable design factors. Simpson demonstrated the use of PPCEM for designing families of electric motors.

The PPCEM requires that the choice of the common and scalable design factors is known a-priori [82], i.e. the method cannot determine which design factors should be common among product family variants. In order to overcome this limitation, Nayak *et al.* proposed a method, named Variation-Based Platform Design Method (VBPDM) [83], which extends the PPCEM to identify the common design factors. In the first stage, the deviations of the design factors are minimised while satisfying the performance requirements. The design factors with small deviations are selected as the platform variables (i.e. common design factors). In the next stage, the product family variants are individually optimised based on the mean values of the platform variables. Nayak *et al.* demonstrated the use of VBPDM for designing a family of electric motors satisfying a range of torque requirements. The main difference between PPCEM and VBPDM is that the VBPDM determines which design factors should be scalable to satisfy the varying performance requirements, whereas the PPCEM requires designers to specify which design factors should be scalable.

Nelson *et al.* proposed a modified two-step approach for designing product families [84]. In the first step, each of product family variants is optimised separately according to the individual family variants' requirements. In the second step, multi-objective optimisation is used to obtain the Pareto sets subject to commonality constraints. Pareto sets enable the designers to decide which components or design factors should be common. The problem with this method is that if the number of variables is large then it would be difficult to compute and visualise all the Pareto sets.

Although the VBPDM enables the designers to achieve optimal trade-off between commonality among product family variants and the individual performances of the variants, the VBPDM does not optimise the commonality and the customisability simultaneously, instead a two-stage approach is used. The two-stage optimisation approach results in suboptimal solutions [85]. This problem was solved by Messac *et al.* by employing physical programming [86], where the product platform (common design factors) and the product family variants (scalable design factors) are optimised simultaneously. A Product Family Penalty Function (PFPF) was introduced that penalises the design factors (during optimisation) which cannot be considered common among the product family variants. With this approach, if a constant value can be assigned to a design factor for all the product family variants with minimum effect on the objectives, then the factor is considered common (platform) among the family variants. On the other hand, if a constant value cannot be assigned to a design factor for all the product family variants without adversely affecting the objectives, then the factor is considered scalable. The PFPF minimises the design variables variations by minimising the percentage variation (pvar). The pvar of the ith design variable is calculated by Equation 2.1.

$$\mathrm{pvar_i} = \frac{\mathrm{var_i}}{\mathrm{\bar{x}_i}} \tag{2.1}$$

where:

$$\mathrm{var_i} = \sqrt{\sum_{\mathrm{j}=1}^{\mathrm{n_p}} \frac{(\mathrm{x_i^j} - \mathrm{\overline{x}_i})^2}{(\mathrm{n_p} - 1)}}, \quad \mathrm{\overline{x}_i} = \sum_{\mathrm{j}=1}^{\mathrm{n_p}} \frac{\mathrm{x_i^j}}{\mathrm{n_p}} \tag{2.2}$$

Here, $\mathrm{x_i^j}$ represents the ith design variable for the jth product variant, and the symbols $\mathrm{n_v}$ and $\mathrm{n_p}$ represent the number of variables and product variants, respectively. The PFPF is calculated by summing all the percentage variations pvar across all the product family variants, i.e. (Equation 2.3).

$$\mathrm{PFPF} = \sum_{\mathrm{i}=1}^{\mathrm{n_v}} \mathrm{pvar_i} \tag{2.3}$$

Simpson and D'Souza proposed a Genetic Algorithm (GA) based method for determining the degree of commonality during product family optimisation [87]. This method does not require the designers to specify common and scalable design factors a-priori. A similar PFPF is used to simultaneously optimise the product platform (common design factors) and the product family variants (scalable design factors).

The above explained product family design methods consider the components or design factors to be either common to all product family variants or to none of them. The effects of this extreme commonality on the performances of the individual product family variants are severe, which does not result in optimal trade-off between commonality and performance [88]. In order to reduce the impact of commonality on the performances of the individual product families, multi-level commonality (MLC) is used. In MLC, components or design factors can be common among few product family variants, rather than be common among all the variants. Huang *et al.* states that a product family design method should consider the multiple levels of commonality during optimisation in order to balance the commonality and the individual performance [85]. Several researchers have introduced MLC in the optimisation process to achieve partial commonality [89] [90] [91] [85].

Most of the product family design methods described above used optimisation-based approach to determine the common design variables and their values. It was discussed in the previous section that the optimisation-based methods cannot handle the changing design requirement. If the requirements change, the whole process of formulating the optimisation problem and execution needs to be started all over again. Furthermore, these 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 optimiser, may be infeasible due to factors not considered by the models such as integration and installation of promising novel technological solutions, which results in costly design rework or iterations later in the design process.

## 2.9 Aircraft Family Design

As discussed in the previous section, product families can be categorised into two types: scale-based and module-based.

In the module-based product families, members of a product family are created by adding, removing or substituting functional modules, i.e. the family members provide different functionalities. Module-based aircraft family design is predominantly conceived for military and Unmanned Air Vehicles (UAVs) [15] where the components are added or substituted to accomplish variety of different functions, e.g. attack/bomber, cargo, surveillance, etc. Figure 2.18 shows an example of a module-based aircraft family, where a cargo variant is created by substituting functional modules.

Figure 2.18: Example of Module-Based Aircraft Family [Source: Cargolux]

In the scale-based product families, members of a family are created by scaling (stretching or shrinking) the components, i.e. all the product family members provide the same functionalities but at the different performance levels. Scaled-based family is conceived for passenger transport aircraft where major components such as fuselage are scaled to accommodate different number of passengers, thus satisfying different airlines' requirements in a cost effective manner. Figure 1.3 shows an example of a scale-based aircraft family, where the wing and empennage are common among all the variants, whereas the fuselage has been shrunk or stretched to satisfy varying numbers of passengers requirement.

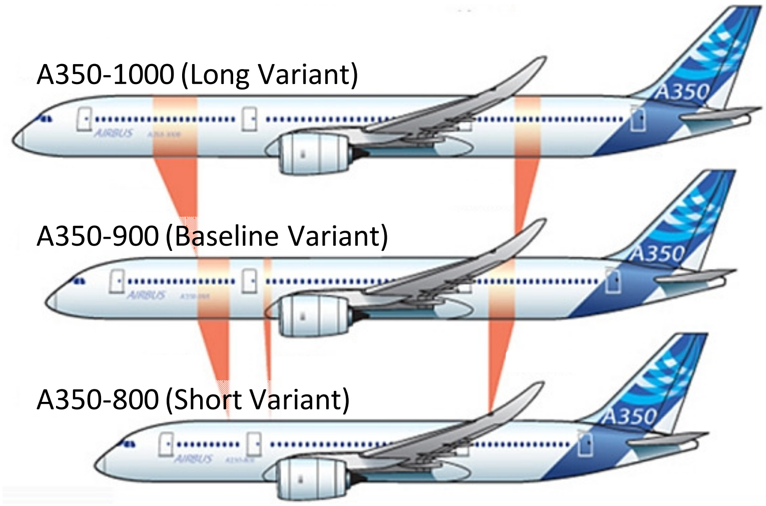


Figure 2.19: Example of Scale-Based Aircraft Family

### 2.9.1 Aircraft Family Trends

The present research focuses only on the scale-based passenger aircraft family design where two Top-Level Aircraft Requirements (TLARs), number of passengers and mission range, are considered for the family creation. The number of passengers and the range for different Airbus and Boeing aircraft families are shown in Figure 1.3. 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 total number of passengers increases, the total range decreases (e.g. Airbus A320 family). In the second trend, more fuel capacity and a higher-thrust engine, but with the same number of passengers result in Extended Range (ER) variants. For example, both Boeing 777-200 and 777-200ER have common fuselage (equal number of passengers), but the later provides longer range. In the third trend, both the number of passengers and the total range are increased by introducing higher-thrust engines and more fuel capacity (e.g. Boeing 777-200 and 777-300). As shown in Fig. 1.3, there is one trend missing (Trend X, shown by a dashed arrow), i.e. increasing the passenger capacity while keeping the range constant (or similar). For instance, currently in order to meet the high demand in Asia, large aircraft such as A340, which are optimised for long range missions, are being used for domestic (short-range) routes, resulting in poor efficiency.

### 2.9.2 Aircraft Family Design Methods

Most of the existing methods, found in literature, for aircraft family design employ sequential, optimisation-based approach where a single optimal design solution is selected quite early in the conceptual design phase and then iteratively modified until it satisfies all the requirements. Willcox and Wakayama [1] developed a Multidisciplinary Design Optimisation (MDO) framework and demonstrated its use for designing BWB aircraft family consisting of two variants. Cabral and Paglione [2] developed a multi-objective optimisation tool for the conceptual design of transport aircraft families using Genetic Algorithms (GA). D'Souza and Simpson [3] also demonstrated the use of GA for designing general aviation aircraft family. Allison et al. [4] used decomposition-based (multi-level) optimisation methods, i.e. Analytical Target Cascading (ATC) and Collaborative Optimisation (CO), for transport aircraft family design. Later, Roth [5] developed an improved and efficient decomposition-based optimisation method, named Enhanced Collaborative Optimisation (ECO) based on CO, and demonstrated its use for designing transport aircraft families. Next, the two MDO architectures, i.e. Analytical Target Cascading (ATC) and Collaborative Optimisation (CO), are explained in detail.

#### 2.9.2.1 Collaborative Optimisation (CO)

Collaborative optimisation (CO) is a method for the design of complex, multidisciplinary systems that was proposed by Braun in 1994 [92] [93] [94]. CO is one of the several decomposition-based methods, which divides the design problem along disciplinary boundaries. Disciplinary analysis tools tend to be complex in nature, and it is often impractical to integrate multiple analysis codes for the purpose of multidisciplinary optimisation. CO , however, offers a means of coordinating separate analyses. The structure of the CO is shown in Figure 2.20. The CO has been used in a variety of engineering design problems. Braun *et al.* [95] and Braun

[96] used the CO for designing launch vehicle design, Manning [97] demonstrated the use of CO for designing high speed civil transport, and Sobieski [93] used it for unmanned air vehicle design. Despite the benefits, CO suffers few problems, especially convergence, as discussed by Alexandrov and Lewis [98].

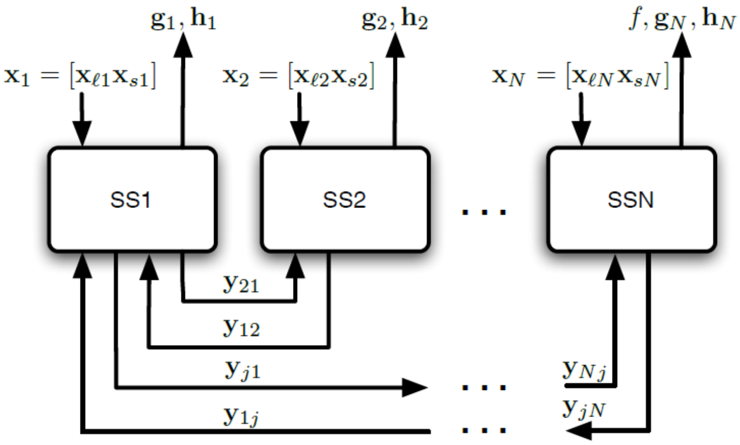


FIGURE 2.20: Collaborative Optimisation Structure [4]

#### 2.9.2.2 Analytical Target Cascading (ATC)

Analytical Target Cascading (ATC) [99] [100] is a multi-level optimisation strategy for the design of complex systems. ATC was specifically developed for design problems with a hierarchical structure. A simplified hierarchical decomposition of the aircraft design problem is illustrated in Figure 2.21, where i represents the level and j represents the element within the hierarchy. The top-level system targets are cascaded through all elements in the hierarchy. The child element analyses generate responses that are inputs to the parent elements. Once the element design specifications are obtained, the individual design tasks may be completed concurrently and independently. As system interactions are considered during the target cascading process, individual design teams can be confident that the system will be consistent and the overall objectives will be met.

Researchers have employed ATC for designing building architecture [102], automotive [103] [104], aircraft[101], and general products [105]. Kokkolaras *et al.* extended the use of ATC for product family design [106]. Allison *et al.* employed ATC for designing aircraft families [4].

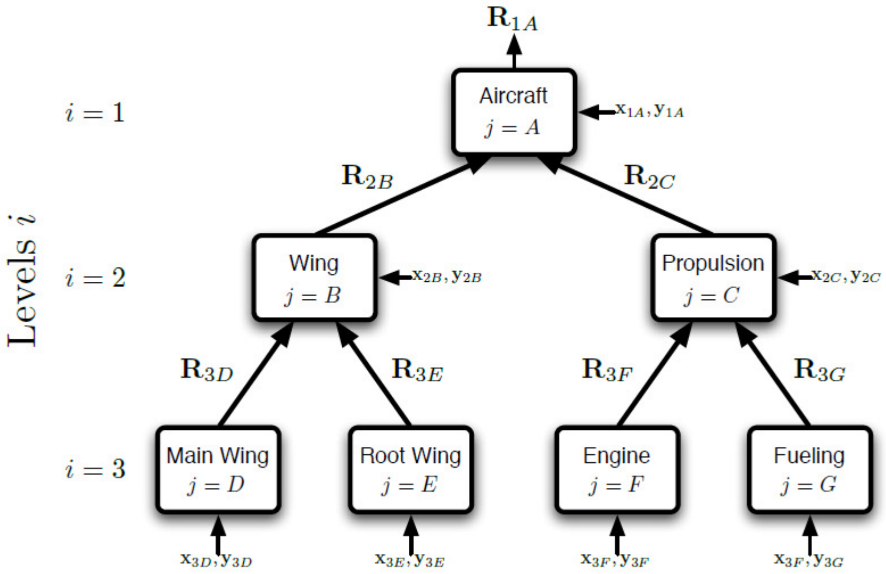


FIGURE 2.21: Analytical Target Cascading (ATC) Hierarchical Structure [101]

One of the problems with ATC is that it faces convergence issues. Michelena *et al.* discusses the convergence issues with ATC [107]. Tosserams [108] and Kim *et al.* [109] proposed the methods for improving convergence in ATC. Furthermore, it is limited to the applications where the designers are reasonably confident about the targets values. Assigning target values to the lower level elements is difficult for innovative aircraft family configurations. The ATC problem would not converge if the assigned targets cannot be met.

The main difference between CO and ATC is in the optimisation process [4] [110]. In CO, nested optimisation is utilised where the system-level optimisation problem is solved only once and the subspaces optimisation problems are solved many times (once for every system-level iteration). On the other hand, in ATC, a sequence of optimisation problems are solved, where a coordination strategy initializes the top-level optimisation problem (with initial guesses for top-level targets), uses the resulting solution to update the target values for the next level down, initializes the problems in the second level, and so on until the bottom level is reached. This process is repeated until convergence.

#### 2.9.2.3 Blended-Wing Body (BWB) Aircraft Family Design Method

Liebeck proposed a way for designing aircraft families for Blended Wing Body (BWB) configuration [111]. Figure 2.22 illustrate the concept for designing aircraft families for the BWB configuration.

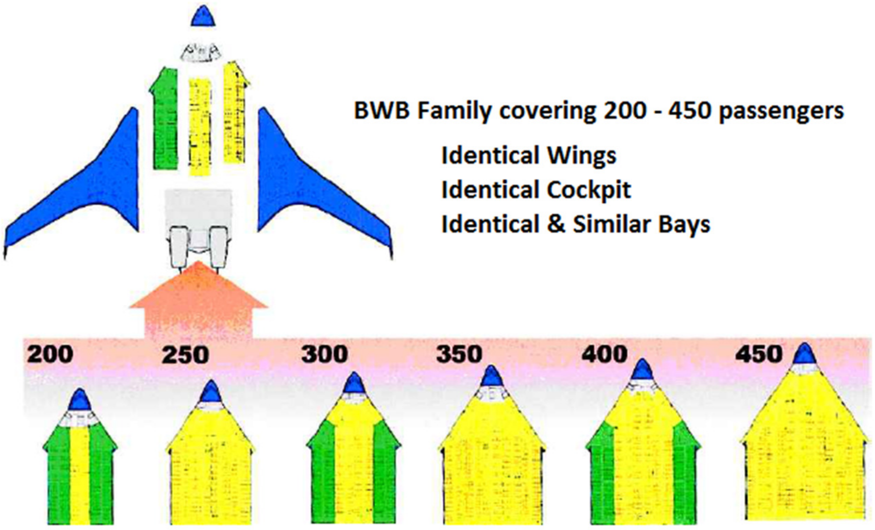


FIGURE 2.22: Blended Wing Body (BWB) Family Covering 200 to 450 Passengers [111]

The passenger capacity is decreased or increased by removing or adding the central bay to the centre-body. As opposed to the longitudinal shrinking or stretching in conventional (tube and wing) aircraft configurations, the shrinking or stretching takes place laterally (spanwise) for the BWB configuration. The wing area and span automatically decrease or increases appropriately with the passenger capacity, a quality not offered by the longitudinal shrinking or stretching for conventional aircraft family. The centre-body cabins are composed of the combinations of two or more distinct cabins (shown in green and yellow colours). The outer wing panels and nose sections (shown in blue colour) are of identical geometry for all the family members. Distinct to each variant are the transition section aft of the nose, the aft centre-body, and the engines (shown in gray colour). Although Liebeck did not present the results for different family variants, it is mentioned that NavierStokes analyses of several of the members of this example family demonstrated proper aerodynamic performance. The aircraft are trimmed and balanced. Finite element modelling was used to quantify the effect of commonality on the structure. The proposed commonality was feasible, but at a cost of increased Operating Empty Weight (OEW) for the smaller aircraft.

In addition, Liebeck presented that the commonality can be extended to the interiors of the BWB configuration. Figure 2.23 illustrate the concept for interior commonality. The cabin cross section is the same for all of the aircraft family variants, which implies common galleys, lavatories, and seating be used.

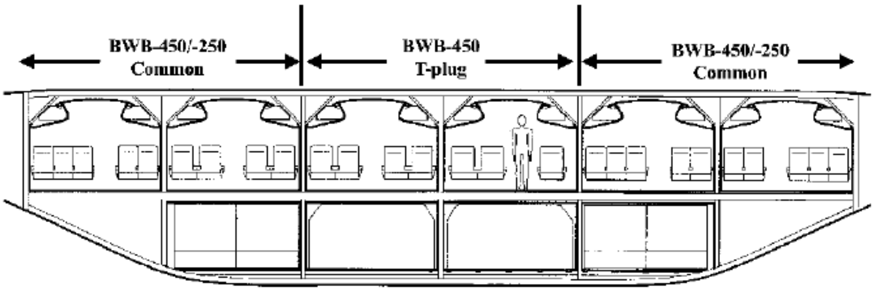


Figure 2.23: Blended Wing Body (BWB) Cabin Cross-Sectional Growth from 200 to 450 Passengers [111]

## 2.10 Summary and Conclusions

Engineering design is a challenging activity which deals with largely ill-defined or ill-structured problems (without having clear goals and objectives, and standard rules to obtain a solution). More importantly, there is no single correct solution to an engineering design problem. Therefore, a good engineering design process (that enables the designers to systematically follow a series of steps in order to come up with a design solution) is a key to the successful design.

In the first part of this chapter, positive and negative points of the different engineering design processes (found in literature) were discussed. The engineering design processes can be classified into two categories: iterative and convergent. Most of the design process models (e.g. French, Pahl & Beitz, Hubka, Pugh, Ullman, spiral, Vee, etc.) are iterative. In the iterative design processes, after clarification of the design specification, a single concept or architecture is selected fairly early by utilizing knowledge from the past projects. The selected concept or architecture is then iteratively analysed and modified until all the requirements are met. One of the problems associated with the iterative design processes is that they involve a large amount of design rework (especially for the innovative concepts or architectures) because limited or imprecise knowledge is used to make critical design decisions very early in the design process. Furthermore, the requirements in the iterative design processes are considered fixed from the start, and the products are designed to meet these fixed requirements. For complex products, such as aircraft, the design phase lasts for many months, which implies that there is a high probability of customer requirements being changed. If the customer requirements change, then the design rework is inevitable. In contrast, the convergent design processes (e.g. Pugh's Total Design, set-based design (SBD), etc.) consider a wider range of design solutions from the outset. The designers then reason about the design solutions by evaluating the performances parameters. Finally, the set of design solutions is gradually reduced by eliminating infeasible and inferior solutions that do not meet the requirements, until a final solution remains.

One of the prevailing convergent design processes, which shows significant potential, is the set-based design (SBD) process (developed by Toyota automotive company). It enables the designers to make better informed decisions by delaying the critical decisions, as more knowledge is gained. In other words, it encourages the designers to foster innovation by preventing them from immediately elaborating on the first concept or architecture that comes into mind, which may not be the best. Furthermore, the SBD process does not require fixed requirements. Instead, the evolving requirements are accommodated, without requiring extra design rework for the changing requirements.

In the second part of this chapter, existing approaches for the design of passenger aircraft families (found in literature) are presented. Two problems were identified with these approaches. The first problem is that these approaches employ sequential and iterative design processes with optimisation-based methods, which have the tendency to exploit assumptions present in the computational models and to drive the design towards a solution which, while promising to the optimiser, may be infeasible due to the factors not considered by the models such as manufacturing, maintenance and novel technologies. These approaches suffer from the convergence issues of the multidisciplinary design optimisation (MDO) architectures. Apart from the optimiser convergence issue, assigning target values required for the MDO architectures, e.g. Analytical Target Cascading (ATC), is not trivial, especially for innovative concepts or architectures where past experience or knowledge is not available. The second identified problem associated with the existing methods for designing passenger aircraft families is that these methods do not consider systems architectures analysis. Aircraft systems play an important role in aircraft family design where the target is to utilise common systems architecture among all the aircraft family variants. The existing methods for designing passenger aircraft families do not provide designers the ability to conduct trade-off between systems architectures and technologies, hence are more suited for aircraft families with conventional systems architecture.

The literature review identified several research gaps. First of all, there is no existing method for designing passenger aircraft families, which uses set-based design (SBD) principles. Although SBD has been applied in Toyota automotive company and US Navy (with reported benefits), there is no formal methodology available in the literature that guides the designers how to implement the SBD process practically. In other words, the existing literature on SBD focuses on defining the principles only, without providing potential enablers or methods for implementing those principles. Enablers for rapidly synthesising and analysing the multitude of design solutions are the key to successfully implement the SBD process. Therefore, there is a need to develop a formal set-based design methodology with potential associated enablers for designing passenger aircraft families. The second identified research gap is that there is no passenger aircraft family design method available that considers systems architectures analysis and design. During the last decade or so, there has been a major trend change in the design of aircraft systems, where new (more-electric) technologies are being introduced. Therefore, there is a need to incorporate systems architectures analysis early into the conceptual design stage in order to conduct trade-off between different systems architectures and technologies. These research gaps were used to define the aim and objectives of the current research, which are listed in Chapter 1.

The next chapter presents a formal methodology for designing passenger aircraft families which embraces SBD principles. In addition, different enablers for implementing SBD principles (either identified from the literature or developed in this research) are presented.

# Chapter 3

# Proposed Methodology

## 3.1 Introduction

In this chapter, a novel methodology for designing passenger aircraft families is presented in order to bridge the gaps identified in Chapter 1 & 2. In Section 3.2, an overview of the proposed methodology is presented. Sections 3.3, 3.4, and 3.5 provides a detailed explanation of the three phases of the proposed methodology. Furthermore, these sections also present several promising tools (either identified or proposed) for each area of the proposed methodology. These tools are adapted and combined to create an effective methodology for designing passenger aircraft families. Finally, Section 3.6 presents the summary of the proposed approach and provides a comparison with the existing methods for designing passenger aircraft families.

## 3.2 Overview of the Proposed Methodology

Existing methods for designing passenger aircraft families employ a sequential "synthesise, analyse, and modify" approach, where the designers select a single concept or architecture fairly early in the design process by making decisions utilizing the past experience. The selected concept or architecture is then iteratively analysed and modified until all the requirements are met. This approach is also termed as Point-Based Design (PBD) because, at any point in the design process, the designers 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 [20] [21] 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 has the advantage of reducing design iterations [45] which result from the decisions made earlier with imprecise knowledge. 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 designers to bring more knowledge early into the conceptual design stage by considering wider design space, resulting in better understanding of the design space through trade-off.

Previous research efforts have presented SBD principles without focusing on how to implement these principles practically. Furthermore, the methods presented are well-suited for designing single products and may not work for product family design. The author is not aware of any method presented for passenger aircraft (or in general any product) family design which uses SBD principles. Therefore, a novel methodology (using SBD principles) for the early design of passenger aircraft families is proposed, as shown in Figure 3.1. The term '*set*', in Figure 3.1, 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 (e.g. actuators, wings, aircraft, etc.) and parameter (e.g. span, area, etc.) ranges.

The proposed passenger aircraft family design methodology is divided into three phases: stakeholder needs mapping, synthesis and analysis, and narrowing-down. The first phase involves the mapping of the stakeholder needs into: 1) performance constraints and 2) initial design variables sets. In the second phase, the design solutions are synthesised at the major components level 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.

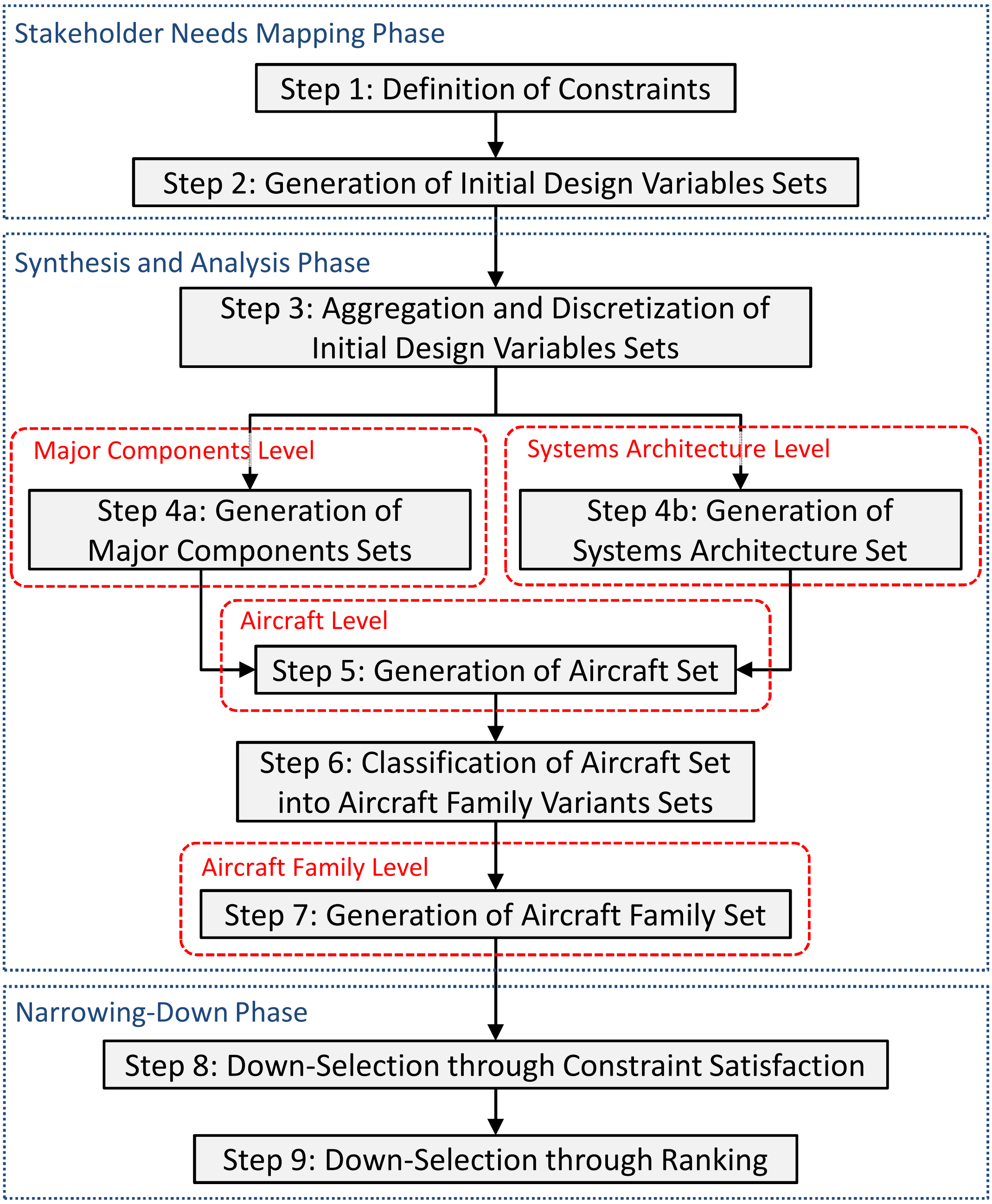


Figure 3.1: Proposed Methodology for Designing Passenger Aircraft Families

The three phases of the proposed passenger aircraft family design methodology, as depicted in Figure 3.1, are further explained step by step in the following sections (Sections 3.3, 3.4, and 3.5). Furthermore, after describing each step, possible promising tools are also presented that may be used to implement the methodology. It is important to note that these tools and enablers are fit for purpose. The designers could also use other tools of their own choice for each step of the proposed methodology.

## 3.3 Phase 1: Stakeholder Needs Mapping Phase

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

### 3.3.1 Step 1: Definition of Constraints

**Description:** In the first step, requirements analysis (as described in engineering standards [53] [54] [55] [56] is used to map the stakeholder needs into performance constraints which are used later during the narrowing-down phase (described in Section 3.5) in order to progressively discard the infeasible aircraft family solutions. The stakeholder needs are the non-measurable requirements expressed in customers own language, which are usually identified by qualitative research, e.g. one-on-one interviews, focus groups, and market surveys and segmentation [112]. The objective of this step is to translate the non-technical stakeholder needs into engineering or technical characteristics that describe the aircraft family. The engineering characteristics are the measurable performance parameters, which are identified by a multidisciplinary team by using domain knowledge and experience [113]. For instance, the stakeholder need for 'efficient' aircraft may be translated into three engineering characteristics: lift-to-drag ratio, specific fuel consumption, and weight. The designers can then focus on improving these engineering characteristics (higher value for lift-to-drag ratio and lower values for specific fuel consumption and weight) which will contribute to meet the above mentioned stakeholder need. The general form of the performance constraints $\mathrm{C_i}$ is given by Equation (3.1) where $\mathrm{C_i}$ is the ith constraint, $\mathrm{c_i}$ is the limiting value for the ith performance constraint, and $\mathrm{n_c}$ is the total number of performance constraints. It should be noted that this step only deals with the performance constraints that are used for evaluating and down-selecting aircraft family solutions quantitatively. Other constraints, e.g. compatibility, geometric, etc., are not considered in this step. Apart from the stakeholder needs, limiting values of the performance constraints must also take account of the competitors' performance.

$$\mathrm{C_i}\begin{cases} = \mathrm{c_i} \\ < \mathrm{c_i} \ , \ \forall \mathrm{i} = 1, \mathrm{n_c} \\ > \mathrm{c_i} \end{cases} \tag{3.1}$$

**Tools/Enablers:** The possible tools and input/output of the 'Step 1' are shown in Figure 3.2. The input to this step is the collection of stakeholder needs whereas the output of this step is the collection of performance constraints $\mathrm{C_i}, \forall \mathrm{i} = 1, \mathrm{n_c}$ for all the aircraft family variants. As shown in Figure 3.2, one of the promising tools that can be used to convert the stakeholder needs into performance constraints is the House of Quality (HoQ) [72], as described in Section 2.7.3

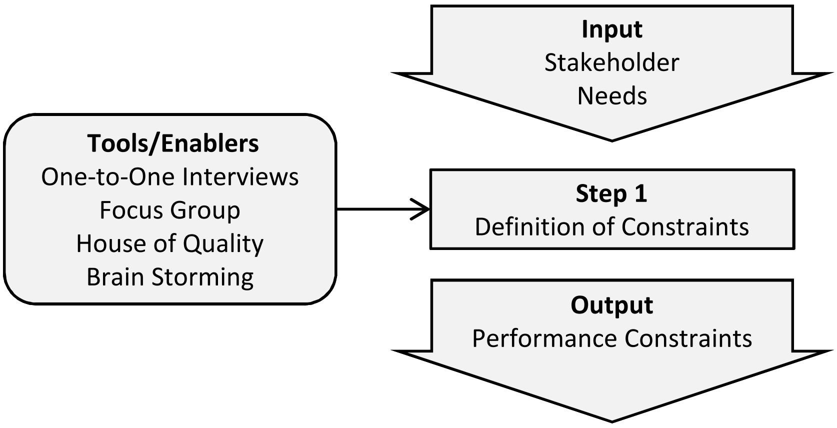


FIGURE 3.2: Step 1: Definition of Constraints

### 3.3.2 Step 2: Generation of Initial Design Variables Sets

**Description:** 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 and experience is the 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 [114]. The general form of the design variable set $\mathrm{V_i}, \forall \mathrm{i} = 1, \mathrm{n_v}$ is given by Equation (3.2) where $\mathrm{D_i}$ is the domain of the ith design variable, and $\mathrm{n_v}$ is the total number of design variables.

$$\mathrm{V_i} := \mathrm{D_i}, \quad \forall \mathrm{i} = 1, \mathrm{n_v} \tag{3.2}$$

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 Equation (3.3) and (3.4), respectively. The lower-case letter $\mathrm{v_i}$ represents an element of the design variable set, i.e. $\mathrm{v_i \in D_i}$. For the discrete design variable set shown in Equation (3.4), $\mathrm{v_{i_k}}$ represent the kth element of the set, i.e. $\mathrm{v_{i_k} \in D_i}$.

$$\mathrm{V_i := D_i = [LB_i, UB_i] = \{v_i \mid LB_i \leq v_i \leq UB_i\}} \tag{3.3}$$

$$\mathrm{V_i := D_i = \{v_{i_1}, v_{i_2}, v_{i_3}, \ldots, v_{i_k}\}} \tag{3.4}$$

For example, the set of wing span $\mathrm{V_1 := [30.0, 40.0]m}$ and the set of wing material $\mathrm{V_2 := \{aluminium, carbonfibre\}}$ are a 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 $\mathrm{V_{WingSpan} := [31.0, 33.0]m \cup [37.0, 39.0]m \cup [39.5, 39.5]m}$.

**Tools/Enablers:** The possible tools and input/output of the 'Step 2' are shown in Figure 3.3. The input to this step is the collection of performance constraints which were obtained in Step 1, whereas the output from this step are the initial design variables sets $\mathrm{V_i, \forall i = 1, n_v}$ for all the aircraft family variants. As shown in Figure 3.3, HoQ can be used to implement this step. In this step, the 'hows' of the HoQ constructed in Step 1 (i.e. performance constraints) become the 'whats' of

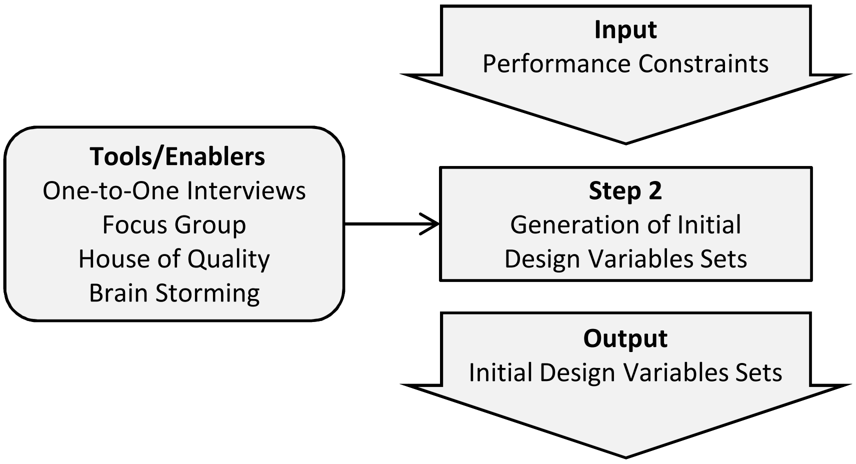


Figure 3.3: Step 2: Generation of Initial Design Variables Sets

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. This is illustrated in Figure 3.4

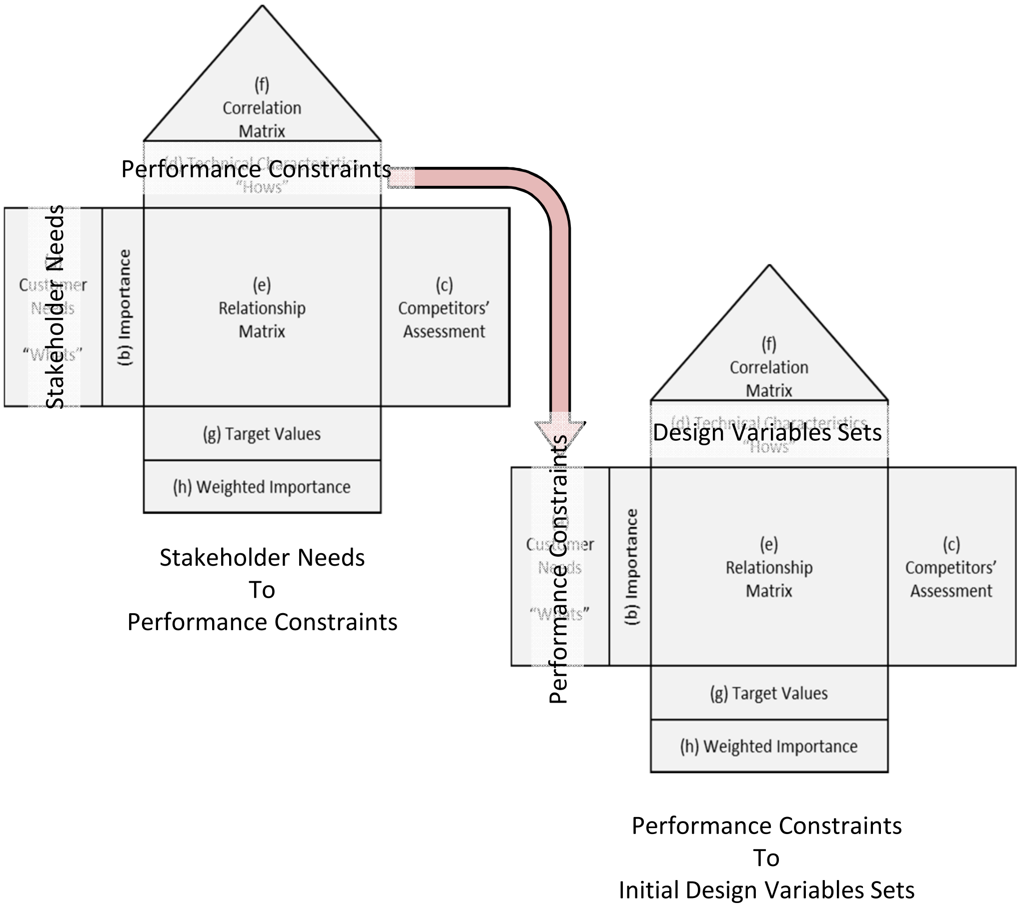


Figure 3.4: House of Quality (HoQ) Structure

## 3.4 Phase 2: Synthesis and Analysis Phase

The second phase of the proposed methodology is concerned with the synthesis and analysis of the aircraft family solutions. 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 or integrated 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 whereas at the systems level, the set of alternative systems architectures is created in order to conduct the trade-off between systems technologies. Next, 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.

### 3.4.1 Step 3: Aggregation and Discretisation of Initial Design Variables Sets

**Description:** The first step in the synthesis and analysis phase is to aggregate all the initial design variables sets $\mathrm{V_i}$, $\forall \mathrm{i} = 1, \mathrm{n_V}$ (obtained in Step 2) of the aircraft family variants. The aggregation process enables employment of 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 $\mathrm{V_i^+}, \forall \mathrm{i} = 1, \mathrm{n_V}$. Mathematically, the ith aggregated design variable set $\mathrm{V_i^+}$ is the union of the ith domains of initial design variables set of the individual aircraft family variants, which is given by Equation (3.5) where $\mathrm{n_{fV}}$ is the number of aircraft family variants and $\mathrm{D_i}$ is the domain of the ith design variable set.

$$\mathrm{V_i^+} := \mathrm{D_i}^+ = (\mathrm{D_i})_1 \cup (\mathrm{D_i})_2 \cup \cdots \cup (\mathrm{D_i})_{\mathrm{n_{fV}}}, \quad \forall \mathrm{i} = 1, \mathrm{n_V} \tag{3.5}$$

For an aircraft family of three variants, $\mathrm{n_{fV}} = 3$ (e.g. Baseline, Short, and Long), the ith aggregated design variables set is given by Equation (3.6) where S, B, and L represents short, baseline, and long variants, respectively.

$$\mathrm{V_i^+} := \mathrm{D_i}^+ = (\mathrm{D_i})_\mathrm{S} \cup (\mathrm{D_i})_\mathrm{B} \cup (\mathrm{D_i})_\mathrm{L}, \quad \forall \mathrm{i} = 1, \mathrm{n_V} \tag{3.6}$$

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 $\mathrm{V^+_{WingSpan}} := [25.0 - 35.0]\mathrm{m} \cup [30.0 - 40.0]\mathrm{m} \cup [35.0 - 45.0]\mathrm{m} = [25.0 - 45.0]\mathrm{m}$.

After aggregation, continuous aggregated design variables sets $\mathrm{V_i^+}$ are discretised in order to achieve a finite number of elements. The discretised aggregated design variables sets are represented by $\mathrm{V_i^{d+}}, \forall \mathrm{i} = 1, \mathrm{n_V}$. The cardinality (number of elements) of the ith discretised aggregated design variables sets $\mathrm{V_i^{d+}}$ 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 $V_i^+$.

**Tools/Enablers:** Figure 3.5 summarises the Step 3 of the proposed methodology. This step is further divided into two steps: first the initial design variables sets are aggregated, and then the continuous aggregated design variables sets are discretised. The tools employed in this step are also shown in Figure 3.5. The union operator is employed for the aggregation and any discretisation strategy can be used to create finite number of elements in the design variables sets.

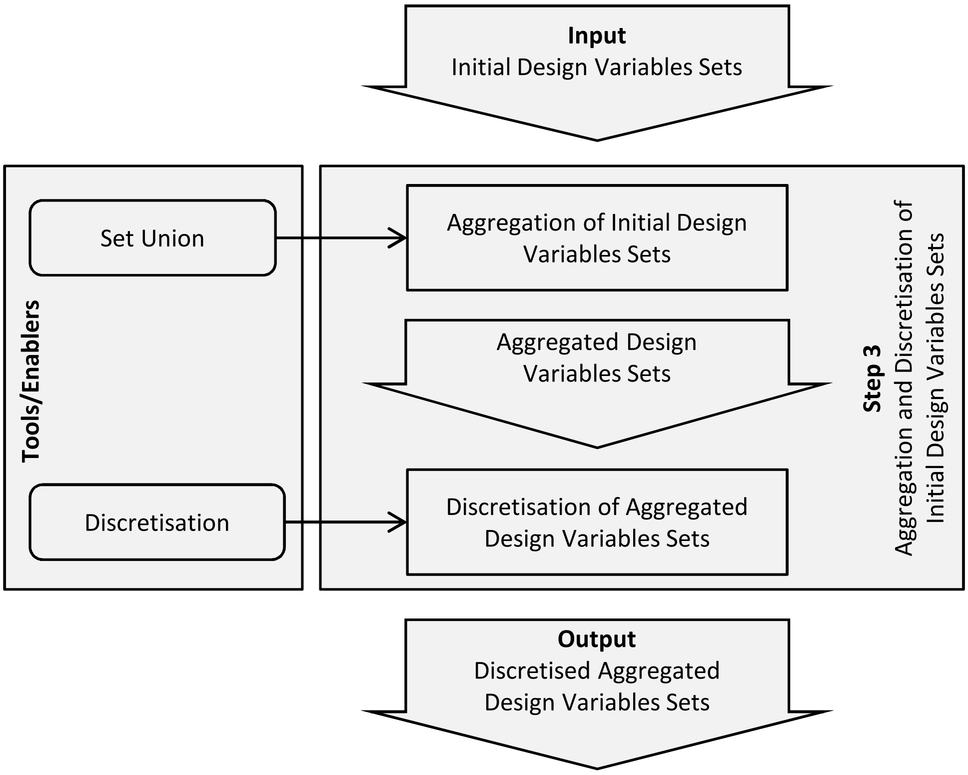


FIGURE 3.5: Step 3: Aggregation and Discretisation of Initial Design Variables Sets

### 3.4.2 Step 4a: Generation of Major Components Sets

**Description:** In this step, the discretised 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 $\mathrm{MC_j}$ is the Cartesian product of the discretised aggregated design variables sets $\mathrm{V_i^{d+}}$ belonging to the jth major component, which is given by Equation (3.7).

$$\begin{aligned} \mathrm{MC_j} &:= \mathrm{V_1^{d+} \times V_2^{d+} \times \cdots \times V_i^{d+} \times \cdots \times V_{n_v}^{d+}}, \\ &\quad \forall \mathrm{j = 1, n_{mc}} \ \mid \ \mathrm{i = 1, n_v} \ \wedge \ \mathrm{V_i \in MC_j} \end{aligned} \tag{3.7}$$

Given n discretised sets $\mathrm{A_1, A_2, \ldots, A_n}$, the Cartesian product (written as $\mathrm{A_1 \times A_2 \times \cdots \times A_n}$) is the set of all the ordered n-tuple $\mathrm{(a_1, a_2, \ldots, a_n)}$ where $\mathrm{a_i \in A_i, \forall i = 1, n}$. Therefore, the cardinality of the jth major component set, represented by $\mathrm{q_j}$, is given by Equation (3.8).

$$\mathrm{q_j = |MC_j| = \prod_{i=1}^{n_v} p_i, \quad \forall j, j = 1, n_{mc} |\ V_i \in MC_j} \tag{3.8}$$

For instance, the two discretised aggregated design variables sets for wing span and area $\mathrm{V_1}^{\mathrm{d+}} := \{30, 40\}\mathrm{m}$ and $\mathrm{V_2}^{\mathrm{d+}} := \{110, 120, 130\}\mathrm{m^2}$, respectively (with $\mathrm{p_1} = 2$ and $\mathrm{p_2} = 3$) will result in the creation of a set of wings with $\mathrm{q_{wing} = p_1 \times p_2} = 2 \times 3 = 6$, i.e. $\mathrm{MC_{wing}} := \{\mathrm{w_1, w_2,\ w_3, w_4,\ w_5, w_6}\} := \{(30, 110),\ (30, 120),\ (30, 130),\ (40, 110),\ (40, 120),\ (40, 130)\}$, where $\mathrm{w_1} = (30, 110)$ (wing with span and area equal to 30m and 110m$^2$, respectively), $\mathrm{w_2} = (30, 120)$, $\mathrm{w_3} = (30, 130)$ and so forth. Apart from synthesizing the set of wings, 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 synthesised and analysed in this step by relevant teams.

**Tools/Enablers:** Figure 3.6 shows the tools and input/output of the Step 4a. The input to this step are the discretised aggregated design variables sets, whereas the output from this step are the sets of all major components. It is important to note that, apart from the discretised aggregated design variables sets, inputs from other major components or systems may be required to determine performance parameters of major components. For instance, in order to determine the mass of the set of landing gears, the mass of the other major components and systems will also be required as input. As shown in Figure 3.6, the identified tool that can be employed to generate sets of major components is Design of Experiment (DOE). DOE is a statistical technique for sampling the design space in a systematic way. It enables the designers to investigate the effects of multiple inputs on one or more outputs [115] which helps to better understand the wider design spaces when limited knowledge is available [116]. There are many sampling approaches for DOE. The simplest but most computationally expensive approach is the full factorial DOE [115] which requires discretisation of the continuous aggregated design variables sets $V_i^+$. Other approaches e.g. Monte Carlo and Latin hypercube etc. [115] are more efficient compared to the full factorial DOE which do not require discretisation, instead the designer needs to specify the number of elements in the major components sets $MC_j$.

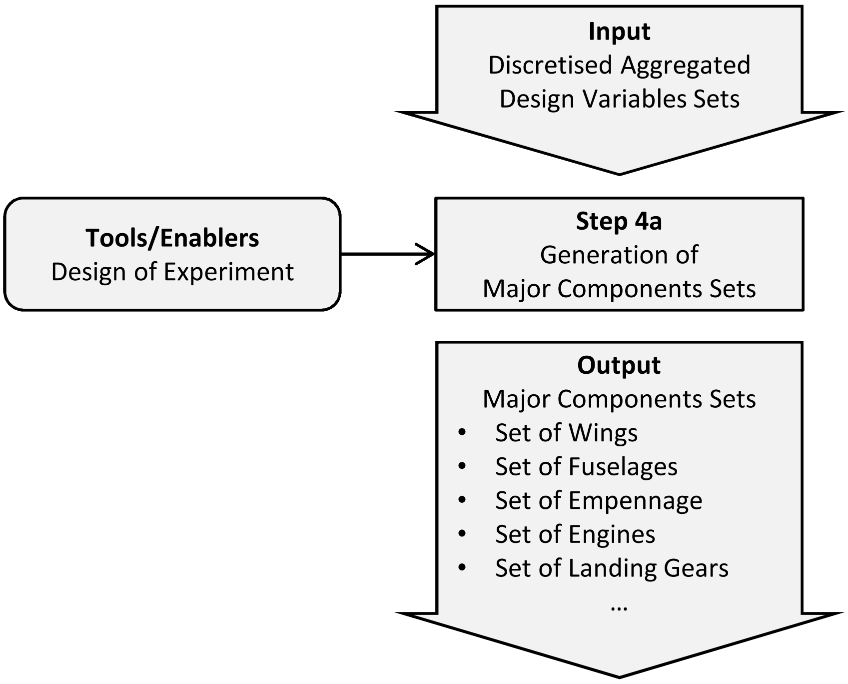


Figure 3.6: Step 4a: Generation of Major Components Sets

### 3.4.3 Step 4b: Generation of Systems Architecture Set

**Description:** This step involves the synthesis and analysis of a set of systems architectures. The set of systems architectures SA is represented by Equation (3.9) 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.

$$\mathrm{SA} = \{\mathrm{sa}_1, \mathrm{sa}_2, \ldots, \mathrm{sa}_{\mathrm{n_{sa}}}\} \tag{3.9}$$

The set of systems architectures SA can be generated by utilizing functional analysis, as described in systems engineering standards [53] [54] [55] [56]. Functional analysis is the process of identifying top-level 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 functions for aircraft systems F is represented by Equation (3.10) where $\mathrm{n_f}$ is the cardinality of the set of decomposed functions for aircraft systems.

$$\mathrm{F} = \{\mathrm{f}_1, \mathrm{f}_2, \ldots, \mathrm{f}_{\mathrm{n_f}}\} \tag{3.10}$$

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; 32]. 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 $\mathrm{X_i}$ is represented by Equation (3.11) where $(\mathrm{x_j})_{\mathrm{f_i}}$ is the jth solution to realise the ith function, and $\mathrm{r_i}$ is the cardinality of the set of physical solutions for the ith function $\mathrm{X_i}$, i.e. $\mathrm{r_i} = |\mathrm{X_i}|$.

$$\begin{aligned} \mathrm{X_i} =& \{(\mathrm{x}_1)_{\mathrm{f_i}}, (\mathrm{x}_2)_{\mathrm{f_i}}, \ldots, (\mathrm{x_j})_{\mathrm{f_i}}, \ldots, (\mathrm{x}_{\mathrm{r_i}})_{\mathrm{f_i}}\}, \\ & \forall \mathrm{i}, \mathrm{i} = 1, \mathrm{n_f} \end{aligned} \tag{3.11}$$

The total number of systems architectures $\mathrm{n_{sa}}$ that can be generated by combining different solutions of all functions is given by Equation (3.12). 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 realise systems functions.

$$\mathrm{n_{sa}} = |\mathrm{SA}| = \prod_{\mathrm{i}=1}^{\mathrm{n_f}} \mathrm{r_i} \tag{3.12}$$

After synthesis, these architectures are analysed using mathematical models in order to conduct trade-off during the ‘narrowing-down phase’ (described in Section 3.5) 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. Fast physics-based computational models can be used to quickly size a large number of architectures.

**Tools/Enablers:** Figure 3.7 shows the tools and input/output of the Step 4b. The input to this step are the discretised aggregated design variables sets, whereas the output from this step is the set of systems architecture. It is important to note that, apart from the discretised aggregated design variables sets, inputs from teams working on other major components or systems may be required to determine performance parameters. For instance, in order to determine the power off-take required for the ‘Environmental Control Systems’ (ECS), (apart from discretised aggregated design variables sets, e.g. number of passengers) the dimensions of the fuselage will also be required as input. As shown in Figure 3.7, the identified tools that can be employed for generating systems architecture set are morphological matrix and function-means tree.

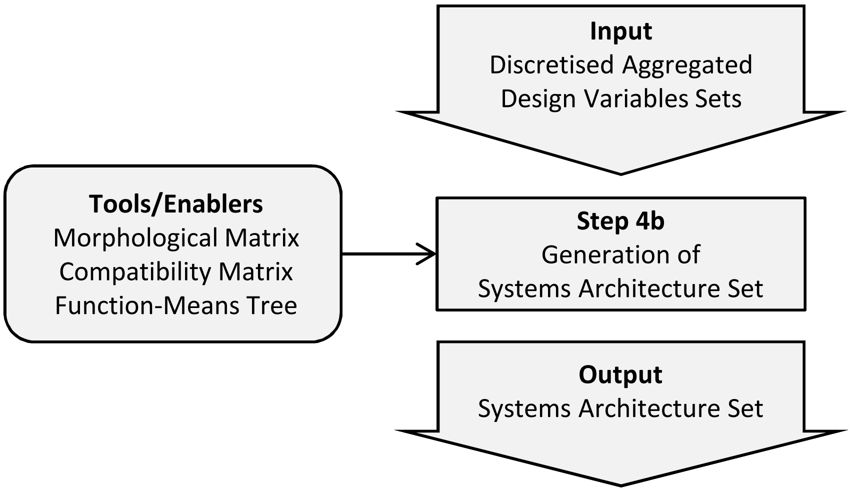


Figure 3.7: Step 4b: Generation of Systems Architecture Set

The morphological matrix [117] [118], 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 and the possible solutions to realize those functions. The structure of the morphological matrix is shown in Figure 3.8. It is created by first listing the set of decomposed functions $\mathrm{F} = \{\mathrm{f}_1, \mathrm{f}_2, \ldots, \mathrm{f}_\mathrm{i}, \ldots, \mathrm{f}_{\mathrm{n}_\mathrm{f}}\}$ in the first column of the matrix, where $\mathrm{n}_\mathrm{f}$ is the total number of decomposed functions. Next, the set of all possible solutions for each function $\mathrm{X}_\mathrm{i} = \{(\mathrm{x}_1)_{\mathrm{f}_\mathrm{i}}, (\mathrm{x}_2)_{\mathrm{f}_\mathrm{i}}, \ldots, (\mathrm{x}_\mathrm{j})_{\mathrm{f}_\mathrm{i}}, \ldots, (\mathrm{x}_{\mathrm{r}_\mathrm{i}})_{\mathrm{f}_\mathrm{i}}\}, \forall \mathrm{i} = 1, \mathrm{n}_\mathrm{f}$ are listed to the right, where $(\mathrm{x}_\mathrm{j})_{\mathrm{f}_\mathrm{i}}$ is the jth solution of the ith function and $\mathrm{r}_\mathrm{i}$ is the total number of available solutions to realise the ith function. It is important to note that the number of solutions for different functions $\mathrm{r}_\mathrm{i}$ do not need to be equal. Furthermore, new or novel solutions, discovered later in the design process, can be added to the morphological matrix without affecting the already conducted analyses. As shown in Figure 3.8, a complete systems architecture, e.g. $\mathrm{sa}_\mathrm{k} = (\mathrm{x}_2)_{\mathrm{f}_1} \oplus \cdots \oplus (\mathrm{x}_1)_{\mathrm{f}_\mathrm{i}} \oplus \cdots \oplus (\mathrm{x}_2)_{\mathrm{f}_{\mathrm{n}_\mathrm{f}}}$, is generated by selecting one solution from each row of the morphological matrix and then combining them together. The symbol $\oplus$ is used to represent the combination of solutions.

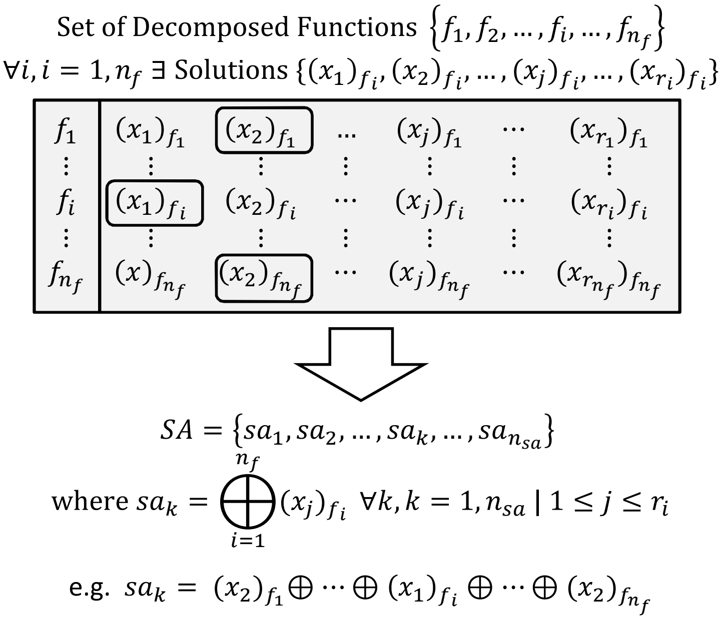


FIGURE 3.8: Morphological Matrix Structure

In practice, however, some of the solutions for one function may not be compatible with some solutions of the other functions, or require some other solutions to be selected as well. The compatibility matrix is, therefore, associated with a morphological matrix to model cross-consistency between different solutions. The general form of the compatibility matrix is shown in Figure 3.9, where n is the total number of the solutions of all functions, and $a_{(i,j)}$ has a value of 0 if the ith and the jth solutions are incompatible, and a value of 1 otherwise. The process of constructing the morphological and compatibility matrix requires experts' opinions and interaction between the disciplinary systems teams.

$$\begin{array}{c|cccc}
 & x_1 & x_2 & \dots & x_n \\
\hline
x_1 & a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\
x_2 & a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
x_n & a_{n,1} & a_{n,2} & \cdots & a_{n,n}
\end{array}$$

$a_{i,j} = 1 \Leftrightarrow$ $x_i$ is compatible with $x_j$

$a_{i,j} = 0 \Leftrightarrow$ $x_i$ is not compatible with $x_j$

FIGURE 3.9: Compatibility Matrix Structure

The decomposed functions can be divided into two categories: top and lower level. The top-level functions are entirely architecture independent, i.e. will be present in every architecture. The selection of a particular solution to realize the top-level function may require other lower-level functions to be introduced. These lower-level functions are architecture specific, i.e. will belong to a particular architecture. Although the morphological and compatibility matrix provide a structured way of representing decomposed functions and their solutions, the dependency among different functions and solutions cannot be captured by morphological matrix. Therefore, function-means tree [119] [120] is employed which presents the functions and solutions or means in a hierarchic manner, helping the designers to discover new solutions. The function-means tree is based on the law of Hubka [121] which states that there are causal relations between functions and solutions. In function-means tree, two types of nodes are used: trapeziums to represent functions and rectangles to represent solutions or means. Figure 3.9 shows the structure of the function-means tree. For each function, there may be multiple means available and similarly there may be multiple functions required to support a particular means. Thus, it is a hierarchical representation of all the possible functions and means, where systems architectures are created by moving along the paths (starting at the root node and moving down to leaf nodes) and selecting a means for each function.

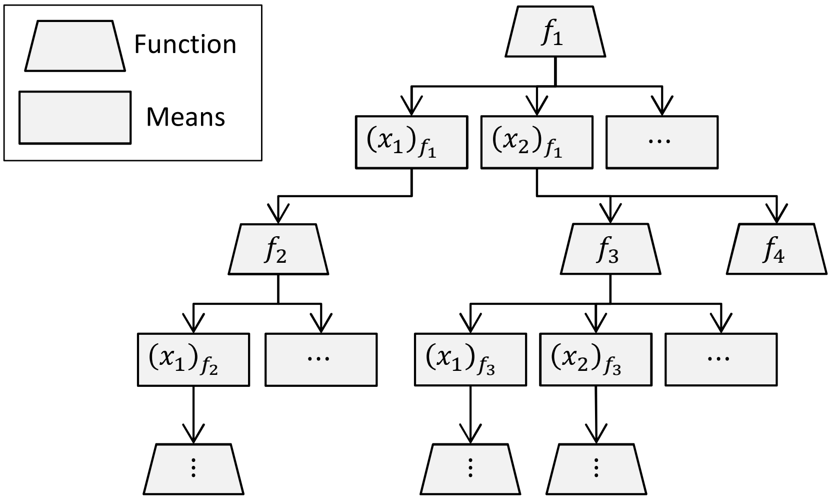


FIGURE 3.10: Function-Means Tree Structure

It is important to note that both morphological matrix and function-means tree could also be served as a knowledge capturing and storing tools.

### 3.4.4 Step 5: Generation of Aircraft Set

**Description:** After generating the sets of major components $\mathrm{MC_j}$ (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 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 Figure 3.1). 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 $\mathrm{MC_j}$ and the set of systems architecture SA, which is given by Equation (3.13). The cardinality of the set of aircraft A is represented by $\mathrm{n_a}$, which is given by Equation (3.14).

$$\mathrm{A = MC_1 \times MC_2 \times \ldots MC_j \cdots \times MC_{n_{mc}} \times SA} \tag{3.13}$$

$$\mathrm{n_a = |A| = n_{sa} \prod_{j=1}^{n_{mc}} q_j} \tag{3.14}$$

For example, the set of aircraft A for six major components sets (fuselage $\mathrm{MC_F}$, wing $\mathrm{MC_W}$, horizontal tail $\mathrm{MC_{HT}}$, vertical tail $\mathrm{MC_{VT}}$, engine $\mathrm{MC_E}$, and landing gear $\mathrm{MC_{LG}}$) and systems architectures set SA is given by Equation (3.15).

$$\mathrm{A} = \mathrm{MC_F} \times \mathrm{MC_W} \times \mathrm{MC_{HT}} \times \mathrm{MC_{VT}} \times \mathrm{MC_E} \times \mathrm{MC_{LG}} \times \mathrm{SA} \tag{3.15}$$

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

**Tools/Enablers:** Figure 3.11 shows the tools and input/output of the Step 5. The input to this step are the major components sets and the systems architecture set, whereas the output from this step is the set of aircraft. As shown in Figure 3.11, the identified tools that can be employed for generating aircraft set are the "Cartesian product" for synthesis, and the "dynamic workflow creation" and "multidisciplinary modelling & simulation" for analysis of the set of aircraft. The analysis involves simulating physical behaviour of the set of aircraft using computational models. The "dynamic workflow creation" method [122] [123] [124] enables the designers to dynamically configure the computational workflows depending on the designers' request for input and output variables, hence providing environment where a large number of aircraft can be analysed quickly.

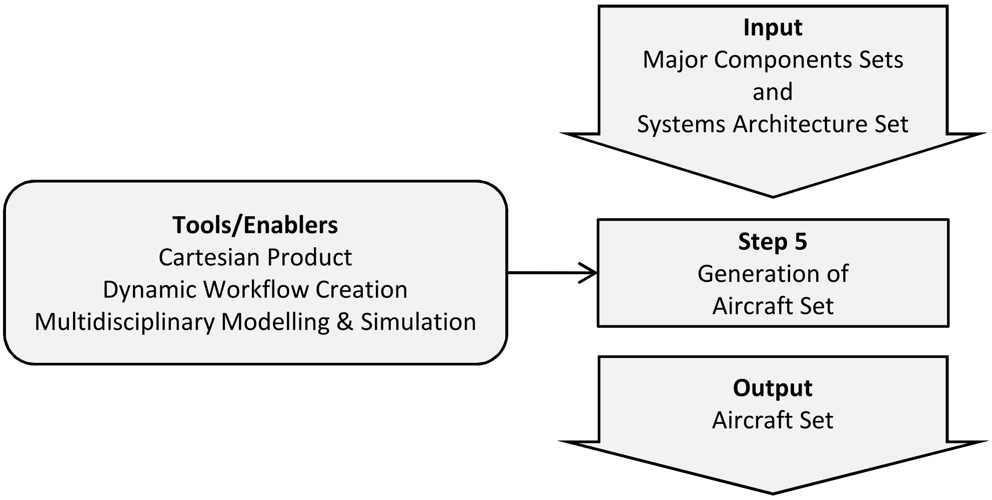


FIGURE 3.11: Step 5: Generation of Aircraft Set

After generating the set of aircraft, the analysis process starts, as shown in Figure 3.12.

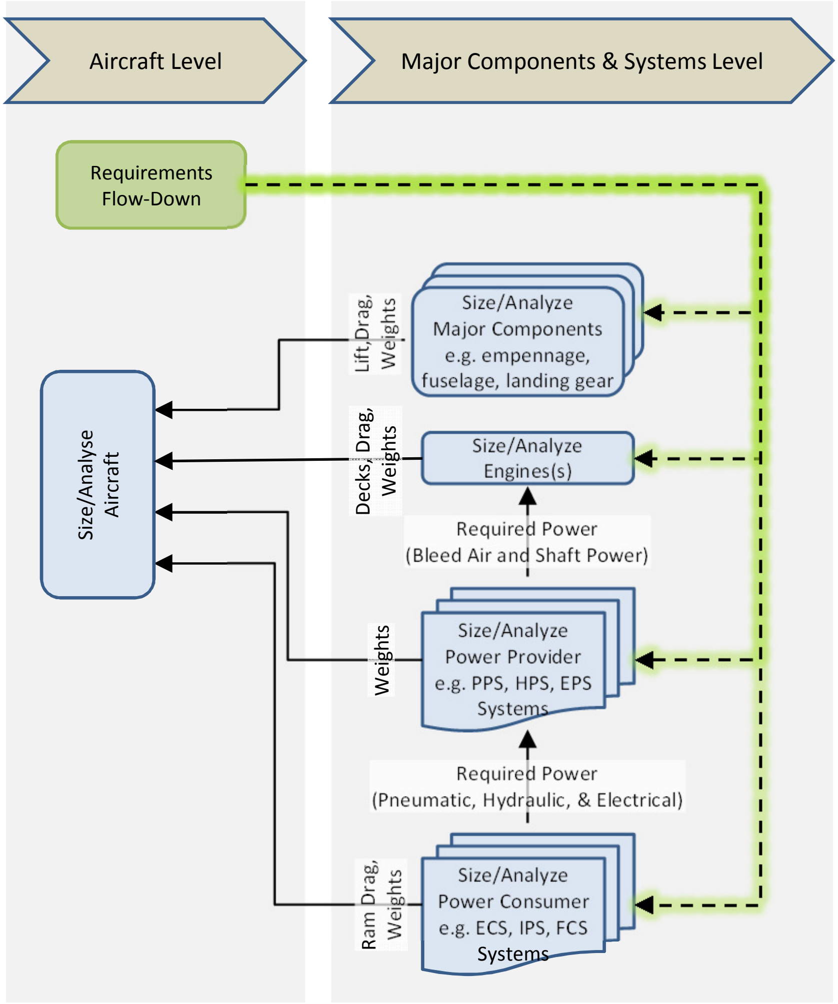


FIGURE 3.12: Aircraft Set Analysis

### 3.4.5 Step 6: Classification of Aircraft Set into Aircraft Family Variants Sets

**Description:** This step is concerned with the classification of the set of aircraft A (obtained in Step 5) into multiple sets $\mathrm{A_k}, \forall \mathrm{k} = 1, \mathrm{n_{fv}}$ corresponding to the desired aircraft family variants where $\mathrm{n_{fv}}$ is the number of aircraft family variants. The aircraft sets for all the family variant $\mathrm{A_k}, \forall \mathrm{k} = 1, \mathrm{n_{fv}}$ are the subset of the set of aircraft A, i.e. $\mathrm{A_k} \subseteq \mathrm{A}$. The classification, as discussed earlier, is based on two design parameters: number of passengers Npax and aircraft range R, which is in line with the actual industrial practices. The set of the aircraft for the kth family variant $\mathrm{A_k}$ is given by Equation (3.16) where a represents an aircraft belonging to the set of aircraft A, $\mathrm{Npax_a}$ and $\mathrm{R_a}$ 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 $\mathrm{min(Npax_k)}$ and $\mathrm{max(Npax_k)}$, respectively. Similarly, $\mathrm{min(R_k)}$ and $\mathrm{max(R_k)}$ 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 $\mathrm{A_B}$ 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.

$$\begin{aligned}\mathrm{A_k} = \Big\{ & \mathrm{a|a \in A \ \wedge min(Npax_k) \leq Npax_a \leq max(Npax_k) \ \wedge} \\ & \mathrm{min(R_k) \leq R_a \leq max(R_k)}\Big\}, \quad \mathrm{\forall k = 1, n_{fv}}\end{aligned} \tag{3.16}$$

The classification parameters (Npax and R) belong to fuselage, therefore, this step subdivides the set of fuselage $\mathrm{MC_F}$ into multiple sets of fuselage corresponding to the aircraft family variants $\mathrm{(MC_F)_k, \forall k, k = 1, n_{fv}}$. For example, considering three aircraft family variants (short, baseline, and long), the set of fuselage $\mathrm{MC_F}$ will be subdivided into three sets of fuselage $\mathrm{(MC_F)_S}$, $\mathrm{(MC_F)_B}$, and $\mathrm{(MC_F)_L}$. The cardinality of the subdivided sets of fuselage is represented by $\mathrm{(q_F)_k, \forall k, k = 1, n_{fv}}$.

**Tools/Enablers:** Figure 3.13 shows the tools and input/output of the Step 6. The input to this step is the aircraft set, whereas the output from this step is

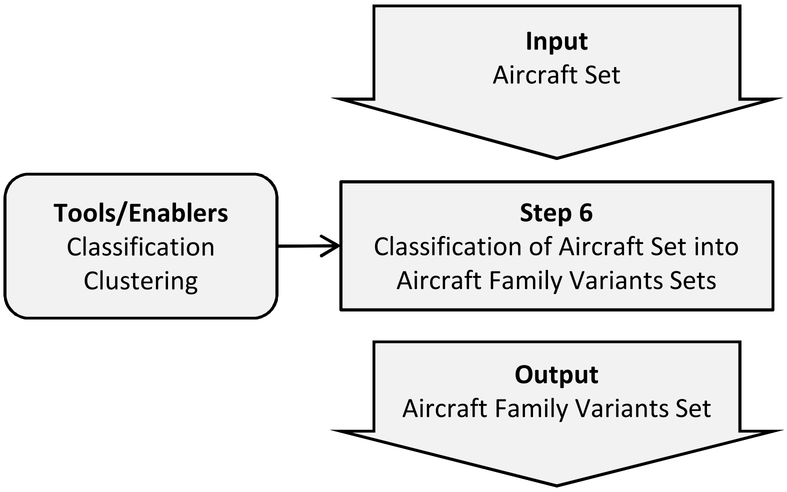


FIGURE 3.13: Step 6: Classification of Aircraft Set into Aircraft Family Variants Sets

the sets of aircraft for each of the family member. As shown in Figure 3.13, the identified tools that can be employed for dividing the set of aircraft into multiple sets of aircraft for family members are the “classification” and “clustering”.

### 3.4.6 Step 7: Generation of Aircraft Family Set

**Description:** The set of aircraft family AF is created by the Cartesian product of the sets of aircraft family variants $(\mathrm{A_v})_\mathrm{i}$ 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.

$$\mathrm{AF} = \{(\mathrm{A_v})_1 \times (\mathrm{A_v})_2 \times \cdots \times (\mathrm{A_v})_{\mathrm{n_{fv}}}\} \tag{3.17}$$

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

$$\mathrm{n_{af}} = \mathrm{n_{sa}} \cdot \prod_{\mathrm{i}=1}^{\mathrm{n_{cv}}} \mathrm{p_i} \cdot \prod_{\mathrm{i}=1}^{\mathrm{n_{ev}}} \prod_{\mathrm{k}=1}^{\mathrm{n_{fv}}} \mathrm{p_{ik}} \tag{3.18}$$

Here, $\mathrm{n_{cv}}$ is the number of common design variables sets, $\mathrm{n_{ev}}$ is the number of exclusive design variables sets, and $\mathrm{n_{fv}}$ is the number of aircraft family variants. Furthermore, $\mathrm{p_{ik}}$ represents the 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 and 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 [9]. 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 synthesising the set of aircraft family AF, the aircraft families are analysed 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 [11].

**Tools/Enablers:** Figure 3.14 shows the tools and input/output of the Step 7. The input to this step are the sets of aircraft for each of the family member, whereas the output from this step is the aircraft family set. As shown in Figure 3.14, the identified tool that can be employed for generating aircraft family set is the "Cartesian Product".

## 3.5 Phase 3: Narrowing-Down Phase

The third phase of the proposed methodology is concerned with the down-selection of aircraft family solutions which are synthesised and analysed in Phase 2. The infeasible and inferior solutions from the aircraft family set are progressively discarded by considering the constraints defined in Phase 1. This phase is comprised of two steps.

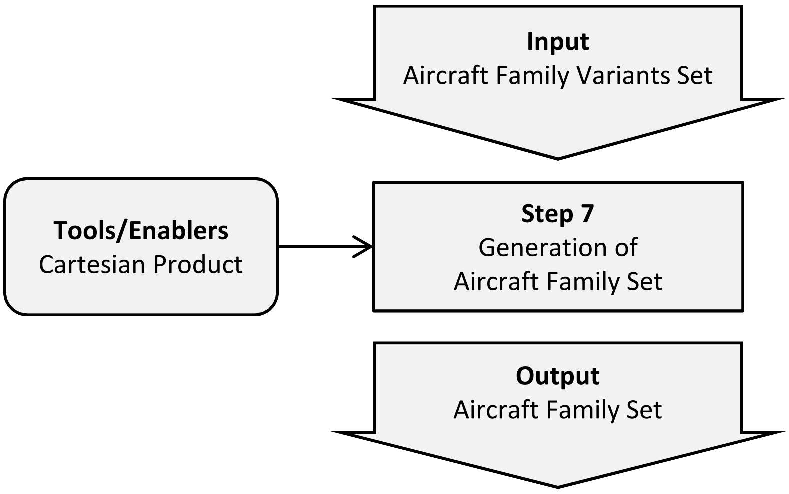


FIGURE 3.14: Step 7: Generation of Aircraft Family Set

### 3.5.1 Step 8: Down-Selection through Constraint Satisfaction

**Description:** 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 $\mathrm{A_i}$, 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 optimisation-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.

**Tool/Enablers:** Figure 3.15 summarises Step 8 of the proposed methodology. The input to this step is the aircraft family set obtained in Phase 2, whereas the output from this step is the reduced subset of aircraft family which is obtained by applying the constraints defined in phase 1.

Figure 3.15 also shows the tools that can be employed for down-selection through constraint satisfaction. A constraint analysis method based on iso-contours is proposed for the down-selection of aircraft family set [125]. The method divides the multi-dimensional design space into multiple 2D projections or slices (contour plots) which show the contour line (also called isoline) of the constraints for two design variables along which the constraint has a constant value [126]. The concept of the constraint analysis using iso-contours is illustrated in Figure 3.16. Here,

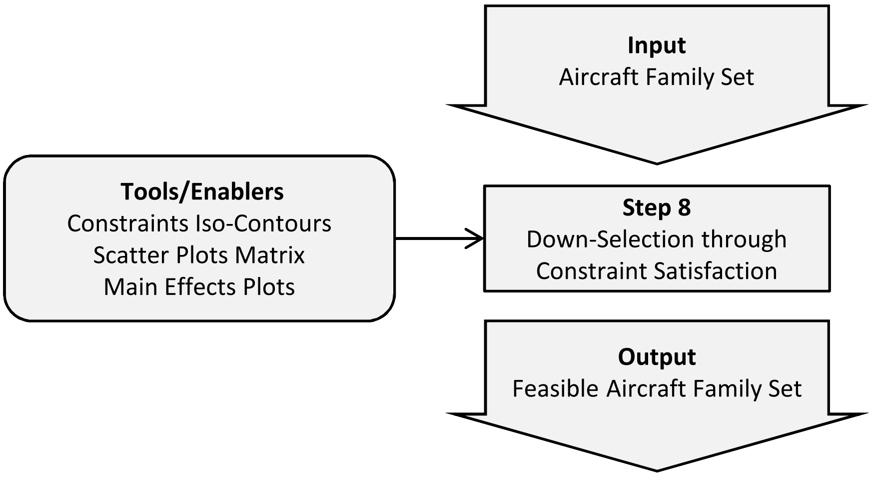


FIGURE 3.15: Step 8: Down-Selection through Constraint Satisfaction

two of the possible 2D slices with iso-contours for maximum take-off weight and nitrogen oxides emissions are shown for the two design variables wing span and wing area by considering different values of sea-level static thrust. The method can be used to generate a matrix of all pairwise 2D contour plots for a number of design variables.

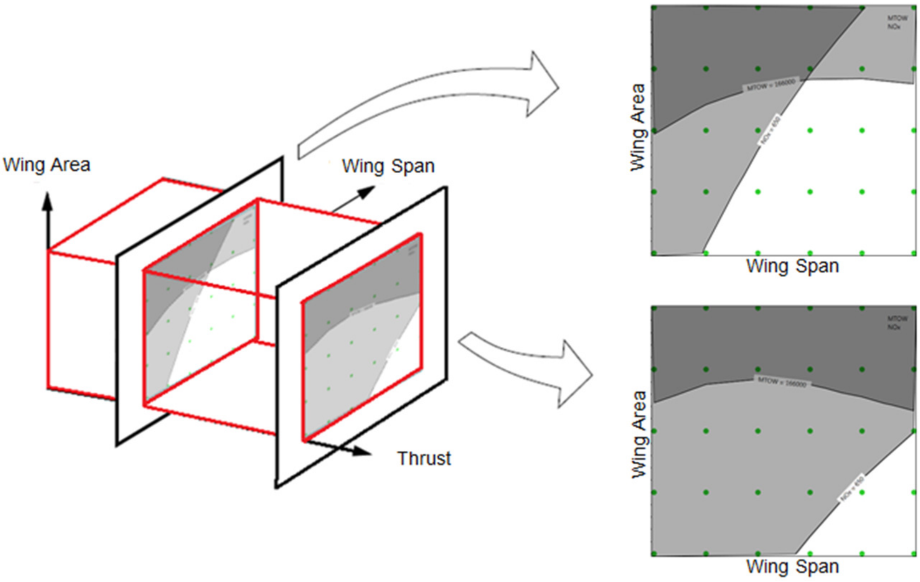


FIGURE 3.16: Constraint Analysis using Iso-Contours

The proposed method does not require new evaluations of the computational models, instead the previously obtained results from the set generation are used by using interpolation in order to compute the constraints iso-contours. This makes the method well suited for the design space exploration at the early stage where designers can interactively move the constraints iso-contours in real-time. Furthermore, it offers the designers flexibility to perform a sensitivity analysis of design variables towards different constraints to invoke what-if analysis in order to better understand the design space. The generalised steps for the construction of the 2D iso-contour plots are given below.

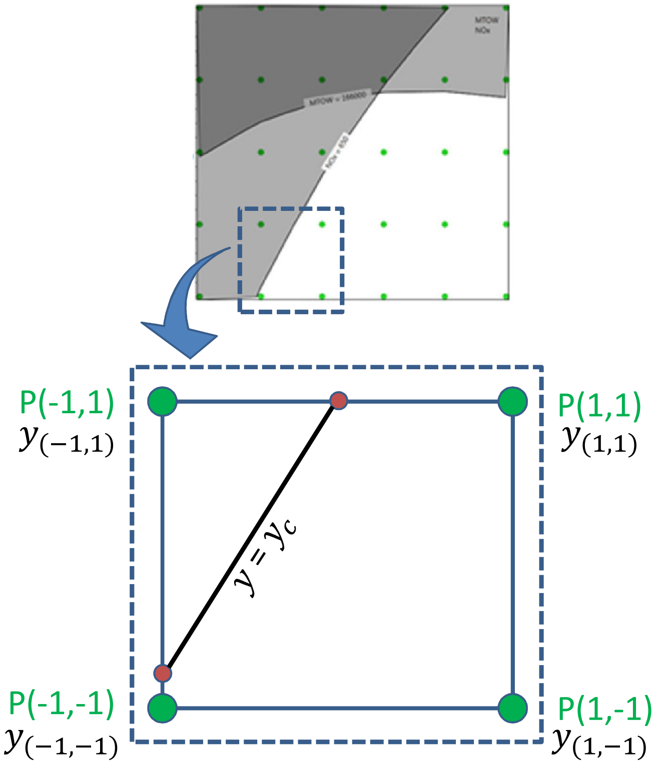


FIGURE 3.17: Calculation of Iso-Contours

1. Given the values of the constraint for the two design variables sets, x and y.
2. The four vertex (corner) points are drawn. The vertex points are $P(-1,-1)$, $P(-1,1)$, $P(1,1)$, $P(1,-1)$. At each vertex point, the average of all the response values at that vertex point is determined: $y_{(-1,-1)}$, $y_{(-1,1)}$, $y_{(1,1)}$, $y_{(1,-1)}$.
3. If there are centre points, a point is drawn at $P(0,0)$ and the average of the response (constraint) values at the centre points is determined.
4. The edges that contain points having values $y = y_0$ are identified. e.g. if $y_{-1,1} \leq y_0 \leq y_{1,1}$, then the top edge contains constraint value.
5. Assuming the linear contour plot (the effect of assuming linear contour plot can be minimised by increasing the number of points in between four vertex

points), $y = \mu + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2$, where $\mu$ is the overall mean of the constraint. The values of $\beta_1$, $\beta_2$, $\beta_{12}$, and $\mu$ are estimated from the vertex points using least squares estimation.

6. In order to generate a single contour line, e.g. for $y = y_0$, where $y_0$ is the limiting value of the constraint for which contour is to be calculated, the $x_2$ is solved in terms of $x_1$ which results in the equation:

$$x_2 = (y_0 - \mu) - \beta_1 x_1 \beta_2 + \beta_{12} x_1 \tag{3.19}$$

A sequence of points for $x_1$ (first design parameter) is used to compute the corresponding values of $x_2$ (second design parameter). These points constitute a single contour line corresponding to $y = y_0$.

Another enabler that can be very useful during the narrowing-down phase is the fast 3D aircraft geometry parametrisation tool that can be used to identify the systems integration issues earlier in the design process. In this research, an interactive 3D geometry parametrisation tool is developed. The tool is based on the earlier work by Kulfan, based on class-shape function transformation (CST) method, which enables to represent 2D geometries as the product of a class function and a shape function [127]. The present research extended the work to include systems architectures as simple 3D primitive shapes (e.g. cuboid, sphere, and cylinders). A more detailed description of the classes and the joining algorithm can be found in references [127] and [128]. The tool uses the object oriented, components-based approach and can be used to build complex aircraft configurations. It allows the designers to conduct conceptual design and analysis without labor-intensive CAD support. Figure 3.18 shows a screen shot of the tool.

### 3.5.2 Step 9: Down-Selection through Ranking

**Description:** 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.

**Tools/Enablers:** Figure 3.19 summarises the Step 9 of the proposed methodology. The input to this step is the feasible aircraft family set obtained in Step 8,

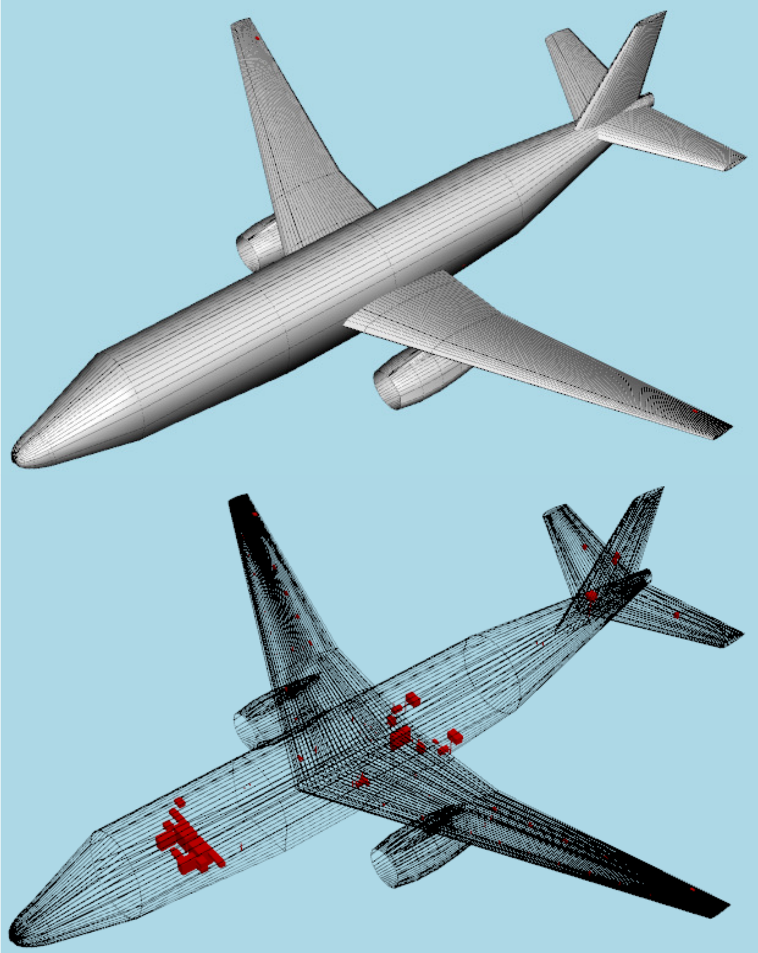


FIGURE 3.18: Aircraft Geometry Parametrisation Tool

whereas the output from this step is the reduced subset of aircraft family which is obtained by applying the ranking based on performance parameters.

Figure 3.19 also shows the two tools that can be employed for down-selection through ranking: Multi-Criteria Decision Analysis (MCDA) and Non-Dominated Sorting. The Multi-Criteria Decision Analysis (MCDA) [129] is a discipline in operations research dealing with the process of decision making in the presence of multiple, potentially conflicting criteria. There are many techniques developed for MCDA [130], one of the very simple and fast technique is Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [131]. It is based on the concept that the chosen alternative should have the shortest Euclidean distance from the positive ideal solution and the longest Euclidean distance from the negative ideal solution. It compares a set of alternatives by normalising scores for each criterion, assigning weights for each criterion, and then calculating the Euclidean distance between each alternative and the best and worst ideal alternative.

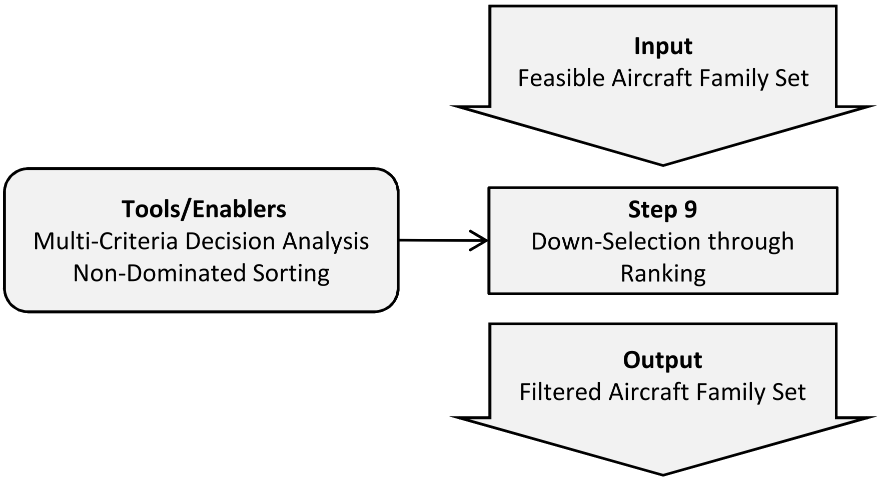


FIGURE 3.19: Step 9: Down-Selection through Ranking

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, in addition to TOPSIS, non-dominated sorting [132] 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 $x_1$ is no worse than $x_2$ in all objectives.
2. The solution $x_1$ is strictly better than $x_2$ in at least one objective.

## 3.6 Summary

Unlike existing methods for designing passenger aircraft families which employ a sequential "synthesise, analyse, and modify" approach, where the designers select a single concept or architecture fairly early in the design process and then focus on iteratively analysing and modifying it until all the requirements are met, the proposed novel methodology keeps the design space open by the parallel development of multiple design solutions and delaying 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, which results in reduced design rework or iterations. Furthermore, the proposed approach incorporates a set of systems architecture which provides designers an environment where they can foster innovation and conduct trade-off between systems technologies by investigating the impacts of system architecture modifications on the aircraft and mission performance. Existing optimisation-based methods e.g. Analytical Target Cascading (described in 2) utilises targets for systems and major components, which makes it very difficult to converge for unconventional design concepts. The proposed methodology does not consider targets, instead a wider design space is explored and then infeasible solutions are simply discarded. The expectation is that the gradual reduction should enable the designers to bring more knowledge early into the conceptual design stage, hence resulting in better understanding of the design space through trade-off.

# Chapter 4

# Application Case-Study

## 4.1 Introduction

In this chapter, the proposed methodology is demonstrated through an application case-study of passenger aircraft family design. The objective of the application case-study is to highlight the capabilities and benefits of the proposed methodology, not to come up with the best design. Furthermore, 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.

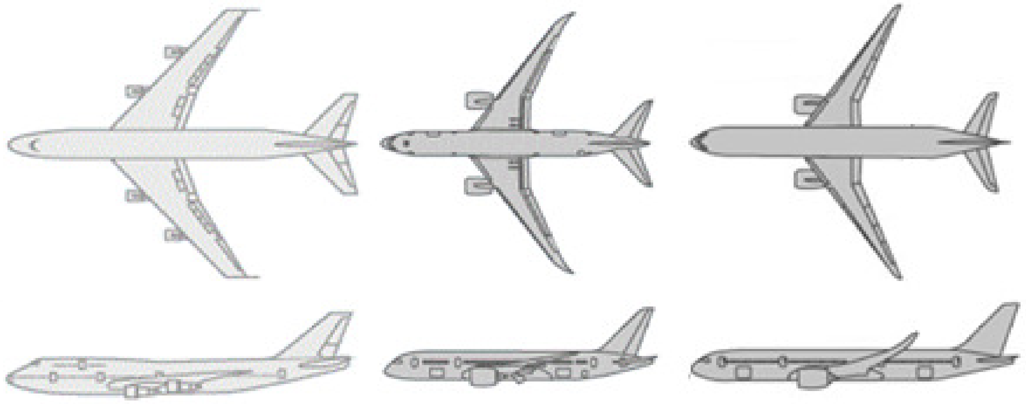
The rest of this chapter is divided into three sections. The application case-study is described in Section 4.2. The individual steps of the proposed methodology are applied to the application case-study in Section 4.3, and finally this chapter is summarised in Section 4.4.

## 4.2 Application Case-Study Description

The passenger aircraft family to be designed is considered to include three members: baseline aircraft, short and long variants. Furthermore, all the family members are considered to have same fuel capacity, where the number of passengers is traded against aircraft range ('Trend 1' in Figure 1.3). The configuration and the systems architectures considered for the application case-study are described next.

### 4.2.1 Configuration

The only civil transport aircraft configuration that has dominated the market over the last six decades is the tube-and-wing configuration that exists in two variations: (a) wing-mounted engines with conventional tail, and (b) fuselage-mounted engines with T-tail. Representative configurations of three civil transport aircraft families are shown in Figure 4.1: the Boeing 747 family was introduced in 1970 and the two latest aircraft families, Boeing 787 and Airbus A350, were introduced in 2011 and 2015, respectively. It becomes clear from Figure 4.1 that both Airbus and Boeing have retained the tube-and-wing configuration for their latest aircraft families.



747
(Introduction: 1970)

787
(Introduction: 2011)

A350
(Introduction: 2015)

Figure 4.1: Latest Configurations for Passenger Aircraft Families

Although there has not been much advancement from a configuration point of view in the last six decades (due to the enormous economic risks involved), greater efficiency has been achieved through improvements in structural materials and primarily propulsion technology. It is expected that the tube-and-wing configuration will be the choice for future civil transport aircraft families until at least 2030 [133]. For this reason, a single-aisle conventional tube-and-wing configuration (low-wing with conventional tail, and two wing-mounted turbofan engines) is considered for the application case-study. Although only one configuration is considered here, the case-study can be easily extended to include set of configurations, e.g. Strut-Braced Wing, Truss-Braced Wing, Joined-Wing, Blended Wing, etc., which is proposed as future work in Chapter 6. Furthermore, all members of the aircraft family are considered to have common wing, empennage (horizontal and vertical tail) and systems architecture, but the fuselages, engines and landing gears are considered exclusive among family members. 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 and weight, and landing gear length will be same, which is in line with the industrial practices for passenger aircraft family design.

### 4.2.2 Systems Architecture

Engines are the main sources of providing power for aircraft. Most of the generated power is propulsive (primary) power that is used for aircraft flight. The remaining power is the non-propulsive (secondary) power that is used for operating aircraft systems. In conventional systems architectures, four types of secondary power (pneumatic, mechanical, hydraulic, and electrical) are used [134], as depicted in Figure 4.2.

Pneumatic power is mainly used by the Environmental Control System (ECS) and Ice Protection System (IPS). Hot air with high pressure and temperature is bled from the engine compressor through one of the two extraction ports. At low engine power setting (e.g. during cruise), bleed air is extracted from High Pressure (HP) stage port, whereas at high engine power setting (e.g. during take-off), bleed air is extracted from Low Pressure (LP) stage port [135]. Although pneumatic power has been used for many years, it is highly inefficient as the bleed air extracted from the engine is over compressed and overheated, i.e. exceeds the safe levels for delivery to downstream components such as the Air Conditioning Pack (ACP). Therefore, a ram air heat exchanger (pre-cooler) is used to achieve the desired low temperature bleed air, discharging excess energy back into the atmosphere as waste heat. The amount of wasted energy can reach up to 30% depending on the operating flight conditions [13]. In addition, the negative effect of bleed air extraction is more severe [10] on high bypass ratio engines which is the current trend in turbofan engine design in order to reduce noise and increase efficiency [136]. Furthermore, it is very difficult to detect bleed air leaks.

Hydraulic power is mainly used by the Flight Control System (FCS), thrust reverser actuation and landing gear (extension or retraction, nose wheel steering during taxing, and brakes). To provide redundancy (required for the primary flight control i.e. roll, pitch, and yaw), two or three separate centralised hydraulic power

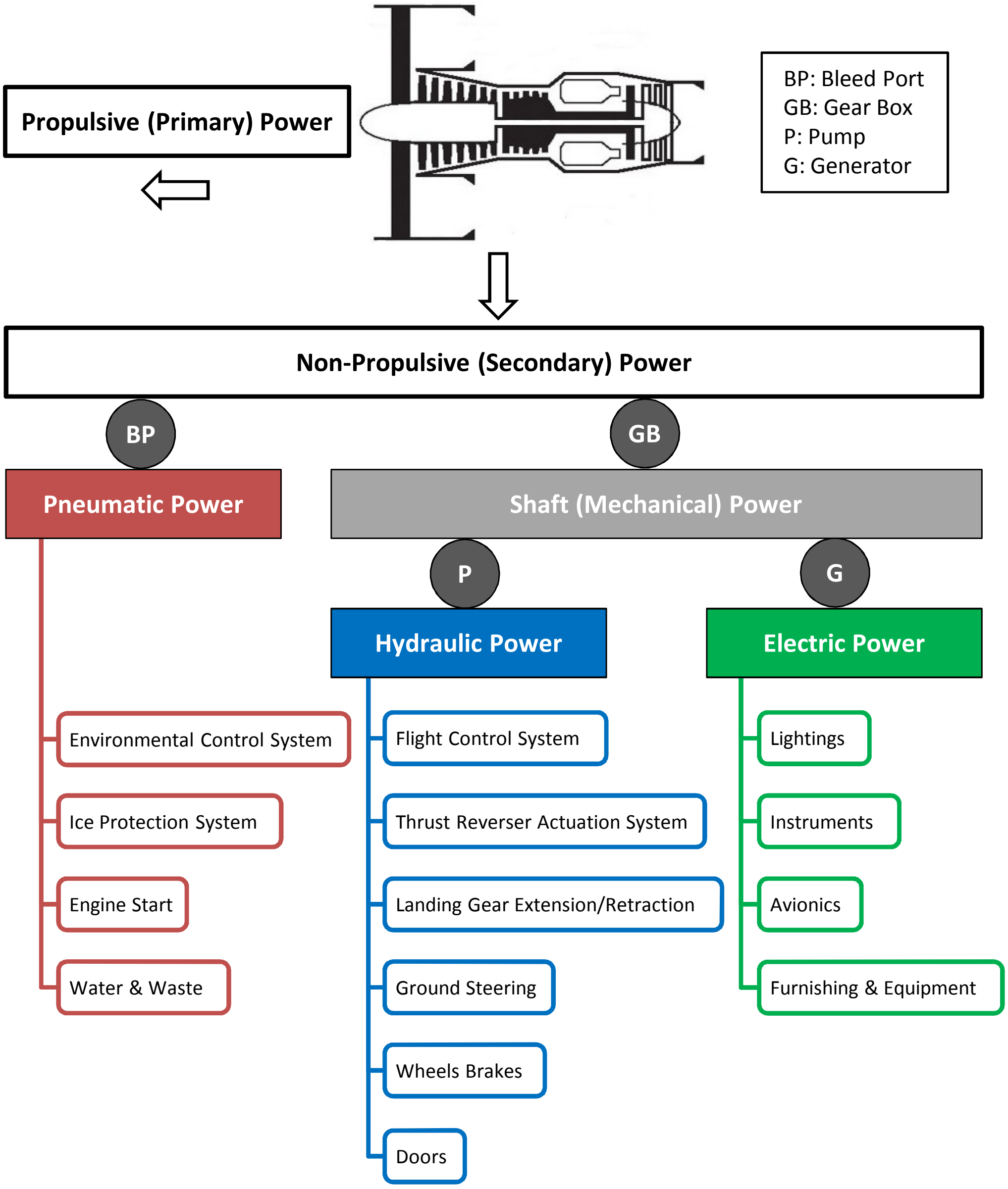


FIGURE 4.2: Power Types used by Conventional Systems Architecture

systems are used. Engine Driven Pumps (EDP) and Electric Motor Driven Pumps (EMDP) are used to pressurise the hydraulic fluid (typically at 3000 – 5000psi). Although hydraulic actuators have higher power-to-weight ratio, heavy components of centralised hydraulic power system (reservoirs, pumps, pipes, etc.), and corrosive and flammable hydraulic fluid are the major drawbacks.

It is important to note that many power consumer systems take more than one type of secondary power, e.g. IPS consumes both pneumatic and electric power, but Figure 4.2 shows only the main type of secondary power required by the conventional systems.

In the last decade or so, there has been a major trend change in the design of aircraft systems. Due to the problems mentioned above, the trend is towards 'All-Electric Aircraft (AEA)' systems architecture, i.e. the use of electrical technologies is increasing for systems which have traditionally been powered by pneumatic, mechanical or hydraulic power. In an AEA systems architecture, all the systems use electrical power for operation, i.e. secondary (non-propulsive) power is solely electric, as depicted in Figure 4.3. The use of electrical power for system allows flexible low-weight routing of components with lower maintenance. In addition, the electric power systems are much easier to monitor system health and status than the hydraulic and pneumatic power systems.

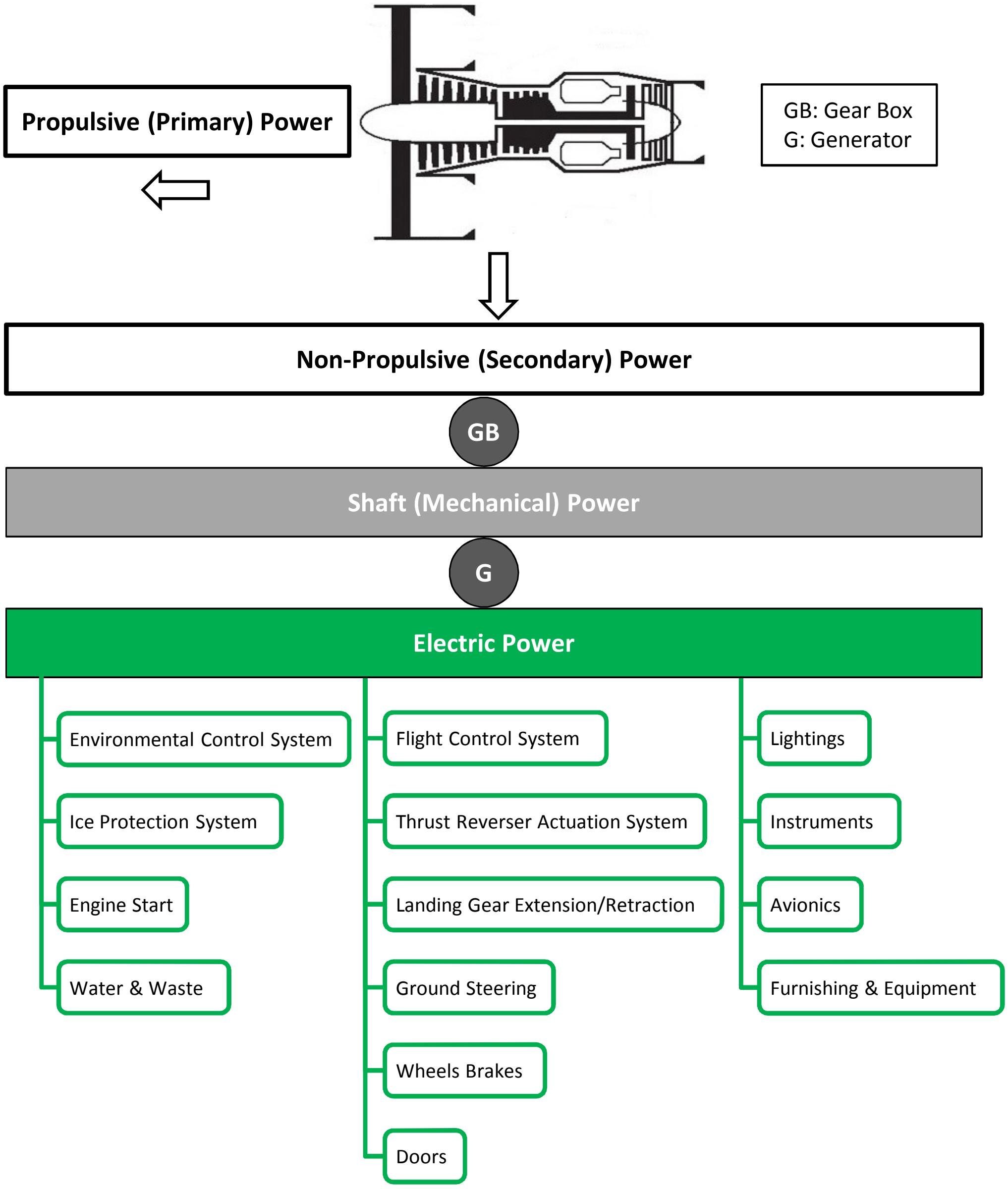


Figure 4.3: Power Types used by All-Electric Systems Architecture

Civil transport aircraft family manufacturers seek evolution (rather than revolution) due to the enormous technological or financial risks involved, therefore currently there is no passenger aircraft family with AEA systems architecture available in the market despite the expected benefits. Instead the transition is progressive, leading to a 'More-Electric Aircraft (MEA)' systems architectures where few (not all) systems are operated by electrical power. For instance, Boeing utilised electrical technologies for 787 ECS and wing IPS, eliminating the Pneumatic Power Systems (PPS) [137]. On the other hand, Airbus utilized Electro Hydrostatic Actuators (EHA) (in parallel with hydraulic actuators) for A380 FCS, reducing hydraulic power use [138]. Apart from electric flight control actuation, Electric Thrust Reverser Actuation System (ETRAS) and electrically actuated brakes have been employed in Airbus A380 and Boeing 787, respectively [139].

Unlike existing methods for designing passenger aircraft families, which select a single systems architecture fairly early and then focus on optimising the architecture, the proposed methodology considers a set of systems architectures. Multiple systems architectures (conventional, AEA, and MEA) are considered in the application case-study, which enables the designers to foster innovation and conduct trade-off between systems technologies.

In the next subsection, the proposed methodology for designing passenger aircraft families will be executed for the application case-study. The nomenclature used for the application case-study is listed in Table 4.1.

| Symbol | Parameter Name | Unit |
|---|---|---|
| N_Pax | Number of Passengers | – |
| N_Pax_E | Number of Passengers (Economy) | – |
| GW | Gross Weight | [lb] |
| Rng | Range | [nm] |
| TWR | Thrust-to-Weight Ratio | - |
| WSR | Wing Loading | [lb/ft$^2$] |
| FASM | Fuel per Available Seat Mile | [lb/nm] |
| TOFL | Take-off Field Length | [ft] |
| LFL | Landing Field Length | [ft] |
| Vapp | Approach Velocity | [kt] |
| FONoise_FO | 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 | [lbf] |
| BPR | Engine Bypass Ratio | - |
| L_MLG | Main Landing Gear Length | [in] |

TABLE 4.1: Application Case-Study Nomenclature

## 4.3 Proposed Methodology Implementation

After describing the application case-study, this chapter is concerned with the implementation of the proposed methodology. The Flight Optimization System (FLOPS) developed by McCullers at NASA [140] [141] has been used for aircraft and mission performance evaluation. FLOPS is a multidisciplinary aircraft sizing and optimisation tool (applicable mainly to conceptual and preliminary design stage). FLOPS aircraft sizing models are limited to conventional systems architecture, therefore, mathematical models for non-conventional (electrical) systems architectures are developed, which are based on several research papers [142] [143] [144] [145] [146] [147] [148] [149] [150] published in literature. These models estimate the masses and the required engine power off-takes (shaft power and bleed-air) in order to determine the effects of systems architectures at aircraft level for trade-off. In addition, an in-house built software, AirCADia [125], is used to obtain the results of the application case-study. AirCADia is an interactive tool for complex systems analysis and design, where computational models from different sources can be used. It automatically links all the concerned computational models and can dynamically configure the computational workflows depending on the designer's request for input and output variables. The details of the method are available in references [122] [123] [124]. It is important to emphasize that the tools or enablers used in this section are not exclusive. The designers may use tools of their own choice for each step of the proposed methodology. In the next three subsections, the steps of the proposed methodology are applied on the application case-study.

## 4.3.1 Phase 1: Stakeholder Needs Mapping Phase

In the first phase, the stakeholder needs are mapped onto (a) the performance constraints and (b) the initial design variables sets. The initial design variables sets will be used later in the 'Synthesis and Analysis Phase' (Section 4.3.2) to generate the set of aircraft family solutions, whereas the performance constraints will be used later in the 'Narrowing-Down Phase' (Section 4.3.3) to progressively discard the infeasible and inferior aircraft family solutions.

### 4.3.1.1 Step 1: Definition of Constraints

In this step, the House of Quality (HoQ) is employed for the definition of performance constraints for all the aircraft family variants. The HoQ is used to translates the stakeholder needs for the transport aircraft family into performance parameters (constraints) for the three variants. These constraints will be used during the narrowing-down phase in order to progressively discard the infeasible design solutions. In order to rank the stakeholder' needs, the importance ratings are evaluated for each of the stakeholder' needs in the scale of between 1 and 10 (1 being the least important and 10 the most important). Analytic Hierarchy Process (AHP), a multi-criteria decision making technique, may be used to rank the stakeholder' needs.

Table 4.2 shows the performance constraints i.e. Equation (3.1) for the application case study, which are obtained from the HoQ. Here, the total number of constraints $\mathrm{n_c}$ is equal to 8, which will be used in Step 8 for down-selection through constraint satisfaction. Table 4.2 also shows the importance of performance constraints, which will be used in Step 9 as weights of the performance parameters for down-selection.

| $c_i$ | Constraint | Criteria | Imp | $(C)_S$ | $(C)_B$ | $(C)_L$ |
|---|---|---|---|---|---|---|
| $c_1$ | N_Pax | > | 10 | 150 | 170 | 190 |
| $c_2$ | Rng | > | 10 | 3500 | 3000 | 2500 |
| $c_3$ | FASM | < | 9 | 0.07 | 0.07 | 0.07 |
| $c_4$ | TOFL | < | 6 | 6600 | 6900 | 7200 |
| $c_5$ | Vapp | < | 6 | 140 | 150 | 160 |
| $c_6$ | FONoise | < | 7 | 82 | 84 | 86 |
| $c_7$ | SLNoise | < | 7 | 82 | 84 | 86 |
| $c_8$ | NOx | < | 7 | 815 | 820 | 825 |

Table 4.2: Constraints for the Aircraft Family Variants

#### 4.3.1.2 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 4.3 lists the initial design variables sets $V_i$ i.e. Equation (3.2) for the application case-study, 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 $(D)_S$, $(D)_B$, and $(D)_L$ for the short, baseline and long variants, respectively, are shown in the last three columns of Table 4.3.

### 4.3.2 Synthesis and Analysis Phase

This phase involves the synthesis and analysis of major components and systems architectures, which are then combined/integrated to create the set of complete aircraft solutions. Next, the set of aircraft is classified into multiple aircraft family variants sets, which are used to create the set of aircraft family.

| $V_i$ | 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 | [1.40 – 2.20] | [1.40 – 2.20] | [1.40 – 2.20] |
| $V_{12}$ | 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] |

TABLE 4.3: Initial Design Variables Sets for the Aircraft Family Variants

#### 4.3.2.1 Step 3: Aggregation of Initial Design Variables Sets

In this step, the union operator, i.e. Equation (3.5), 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 4.3. The resulting domains of aggregated design variables sets $D_i^+$ are shown in Table 4.4. All the initial design variables sets are continuous, therefore the domains of the aggregated design variables sets $D_i^+$ are discretised (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 4.4. This step does not stipulate any requirement on the cardinality of the discretised aggregated design variables sets $p_i$, although higher cardinality increases the time required for modelling and simulation.

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 higher bypass ratio engines while keeping the airframe and systems the same. In order to demonstrate such capability, it is assumed that the empennage will be reused from the existing aircraft family.

| $V_i$ | 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 | $[4.00 - 6.00]$ | $\{4.00, 4.50, 5.00, 5.50, 6.00\}$ | 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 | $[1.40 - 2.20]$ | $\{1.40, 1.60, 1.80, 2.00, 2.20\}$ | 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 | $[117.0 - 120.0]$ | $\{117.0, 120.0\}$ | 2 |

TABLE 4.4: Aggregation and Discretisation of Initial Design Variables Sets

Therefore, the discretised aggregated design variables sets belonging to horizontal and vertical tails ($V_6$ to $V_{13}$) are reduced to a single fixed values, i.e. $p_i = 1$, $\forall i = 6$ to 13. The values of the empennage parameters are listed in Table 4.5.

| Symbol | Design Variable Name | Unit | Values |
|---|---|---|---|
| S_HT | Horizontal Tail Reference Area | $ft^2$ | 335.0 |
| AR_HT | Horizontal Tail Aspect Ratio | - | 5.00 |
| TR_HT | Horizontal Tail Taper Ratio | - | 0.25 |
| phi_HT | Horizontal Tail Sweep Angle | deg | 29.0 |
| S_VT | Vertical Tail Reference Area | $ft^2$ | 230.0 |
| AR_VT | Vertical Tail Aspect Ratio | - | 1.80 |
| TR_VT | Vertical Tail Taper Ratio | - | 0.30 |
| phi_VT | Vertical Tail Sweep Angle | deg | 34.0 |

TABLE 4.5: Design Parameters for Empennage

#### 4.3.2.2 Step 4a: Generation of Major Components Sets

In this step, the Design of Experiment (DOE) 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 designers to investigate the effects of multiple inputs on one or more outputs which helps to better understand the wider design spaces when limited knowledge is available. There are many sampling approaches for DOE. The simplest but most computationally expensive approach is the full factorial DOE [115] which requires discretisation of the continuous aggregated design variables sets $V_i^+$. Other approaches e.g. Monte Carlo, fractional factorial, and Latin hypercube etc. [115] are more efficient compared to the full factorial DOE which do not require discretisation, instead the designer needs to specify the number of elements in the major components sets $MC_j$. This step does not stipulate a particular DOE approach or how the design variables sets should be discretised. For the current application case-study, full factorial DOE is used.

The major components for the application case-study 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 Equation (3.7). For instance, in Table 4.4, four discretised aggregated design variables sets ($V_2^{d+}$, $V_3^{d+}$, $V_4^{d+}$ and $V_5^{d+}$ with cardinalities $p_3 = 5$, $p_4 = 4$, $p_5 = 2$, and $p_6 = 3$, respectively) belong to wing. By using Equation (3.7), 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 Equation (3.8). In order to reduce the modelling and simulation activities for the application case-study, only three discretised aggregated design variables sets, i.e. sets of wing area, aspect ratio, and thickness-to-chord ratio ($V_2^{d+}$, $V_3^{d+}$, and $V_4^{d+}$), are considered for the creation of set of wings. The discretised aggregated design variables set of wing sweep is reduced to a single fixed values, i.e. $V_5^{d+} = \{25.0\}$ with $p_5 = 1$. 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 synthesizing, the set of wings is analysed to evaluate performance parameters such as mass and cost. The set of wings $MC_W$ for the thickness-to-chord ratio of 0.10, generated using Equation (3.7), is shown in Table 4.6, where M_W and FuelCap_W represent the mass and fuel capacity, respectively.

| Wing | S_W [$ft_2$] | AR_W – | M_W [lb] | FuelCap_W [lb] |
|---|---|---|---|---|
| $w_1$ | 1300.0 | 8.0 | 1258.9 | 32341 |
| $w_2$ | 1300.0 | 9.0 | 1266.6 | 32461 |
| $w_3$ | 1300.0 | 10.0 | 1273.9 | 32522 |
| $w_4$ | 1300.0 | 11.0 | 1280.8 | 32656 |
| $w_5$ | 1325.0 | 8.0 | 1338.4 | 33237 |
| $w_6$ | 1325.0 | 9.0 | 1346.6 | 33365 |
| $w_7$ | 1325.0 | 10.0 | 1354.3 | 33467 |
| $w_8$ | 1325.0 | 11.0 | 1361.3 | 33588 |
| $w_9$ | 1350.0 | 8.0 | 1419.5 | 34067 |
| $w_{10}$ | 1350.0 | 9.0 | 1428.2 | 34178 |
| $w_{11}$ | 1350.0 | 10.0 | 1436.4 | 34288 |
| $w_{12}$ | 1350.0 | 11.0 | 1444.2 | 34398 |
| $w_{13}$ | 1375.0 | 8.0 | 1502.2 | 35801 |
| $w_{14}$ | 1375.0 | 9.0 | 1511.4 | 35922 |
| $w_{15}$ | 1375.0 | 10.0 | 1520.0 | 36098 |
| $w_{16}$ | 1375.0 | 11.0 | 1528.3 | 36201 |
| $w_{17}$ | 1400.0 | 8.0 | 1586.5 | 37428 |
| $w_{18}$ | 1400.0 | 9.0 | 1596.1 | 37546 |
| $w_{19}$ | 1400.0 | 10.0 | 1605.2 | 37666 |
| $w_{20}$ | 1400.0 | 11.0 | 1614.0 | 37723 |

TABLE 4.6: Major Components Set for Wings ($MC_W$)

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 the function of Maximum Take-Off Weight (MTOW) [11] [61]. These models are not suitable for aircraft family design because using common component will result in a 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, TCR_W, etc.), rather than MTOW.

Similarly, the set of fuselages $\mathrm{MC_F}$ is generated by using Equation (3.7). In Table 4.4, only one discretised aggregated design variables set ($\mathrm{V_1^{d+}}$ with cardinality $\mathrm{p_1} = 7$) belongs to fuselage. This results in the creation of the set of fuselage $\mathrm{MC_F}$ with cardinality $\mathrm{q_F}$ equal to 7, as shown in Table 4.7, where M_F and PaxCap_F represent the mass and passenger capacity (single-class) of the fuselages, respectively.

| Fuselage | L_F [ft] | M_F [lb] | PaxCap_F |
|---|---|---|---|
| $\mathrm{f_1}$ | 115.0 | 1653.1 | 129 |
| $\mathrm{f_2}$ | 120.0 | 1725.0 | 141 |
| $\mathrm{f_3}$ | 125.0 | 1796.9 | 154 |
| $\mathrm{f_4}$ | 130.0 | 1868.7 | 166 |
| $\mathrm{f_5}$ | 135.0 | 1940.6 | 178 |
| $\mathrm{f_6}$ | 140.0 | 2012.5 | 191 |
| $\mathrm{f_7}$ | 145.0 | 2084.4 | 203 |

TABLE 4.7: Major Components Set for Fuselages ($\mathrm{MC_F}$)

As mentioned earlier (in Step 3) that the empennage will be reused from the existing aircraft family. By using the design parameters listed in Table 4.5, 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 Equation (3.7), as described earlier. In Table 4.4, two discretised aggregated design variables sets ($\mathrm{V_{14}^{d+}}$ and $\mathrm{V_{15}^{d+}}$ with cardinality $\mathrm{p_{14}} = 6$ and $\mathrm{p_{15}} = 3$) belong to engine, whereas only one discretised aggregated design variables set ($\mathrm{V_{16}^{d+}}$ with cardinality $\mathrm{p_{16}} = 2$) belongs to landing gear. This results in the creation of the set of engine $\mathrm{MC_E}$ and landing gear $\mathrm{MC_{LG}}$ with cardinalities $\mathrm{q_E}$ and $\mathrm{q_{LG}}$ equal to $6 \times 3 = 18$ and 2, respectively. After synthesising, the sets of engines $\mathrm{MC_E}$ and landing gears $\mathrm{MC_{LG}}$ are analysed to evaluate performance parameters such as mass and cost. It is important to note that performance evaluation may require inputs from teams synthesising 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.

The major components, their belonging initial design variables sets and cardinalities are listed in Table 4.8.

| j | Major Components | $V_i$ | $q_j$ |
|---|---|---|---|
| 1 | Fuselage | $V_1$ | 7 |
| 2 | Wing | $V_2, V_3, V_4, V_5$ | 40 |
| 3 | Horizontal Tail | $V_6, V_7, V_8, V_9$ | 1 |
| 4 | Vertical Tail | $V_{10}, V_{11}, V_{12}, V_{13}$ | 1 |
| 5 | Engine | $V_{14}, V_{15}$ | 18 |
| 6 | Landing Gear | $V_{16}$ | 2 |

TABLE 4.8: Cardinalities of Major Components Sets

#### 4.3.2.3 Step 4b: Generation of Systems Architecture Set

In this step, two enablers are employed for the generation of systems architectures set: (a) morphological matrix and (b) function-means tree. The morphological matrix [117] [118], 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 [53] [54] [55] [56]) and the possible solutions to realize those functions. A solution may be either a single component or a group of components connected together to perform a particular function. 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 by a morphological matrix. Therefore, function-means tree [119] [120] is employed, which presents the functions and solutions or 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 be served as a knowledge capturing and storing tools. Figures 4.4 and 4.5 show the notional morphological matrix and functions-means tree, respectively.

Systems architecture is an ensemble of 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

| **Decomposed Functions** | **Solutions** | | | | $r_i$ |
|---|---|---|---|---|---|
| $f_1$: Condition Air for Cabin | $(x_1)_{f_1}$Turbofan Air Cycle | $(x_2)_{f_1}$Bootstrap Air Cycle | $(x_3)_{f_1}$Reversed Bootstrap Air Cycle | | 3 |
| $f_2$: Condition Air for E/E Bay | $(x_1)_{f_2}$Turbofan Air Cycle | $(x_2)_{f_2}$Bootstrap Air Cycle | $(x_3)_{f_2}$Reversed Bootstrap Air Cycle | $(x_4)_{f_2}$Vapour Cycle | 4 |
| $f_3$: Provide Compressed Air | $(x_1)_{f_3}$Bleed-Air | $(x_2)_{f_3}$Ram Air with Electric Compressor | | | 2 |
| $f_4$: Provide Coolant | $(x_1)_{f_4}$R-134 | | | | 1 |
| $f_5$: Protect Wing from Ice | $(x_1)_{f_5}$Hot Bleed-Air | $(x_2)_{f_5}$Electro-Thermal | $(x_3)_{f_5}$Pulse Electro-Thermal | $(x_4)_{f_5}$Electromechanical Expulsive | 4 |
| $f_6$: Protect Engine Cowling from Ice | $(x_1)_{f_6}$Hot Bleed-Air | $(x_2)_{f_6}$Electro-Thermal | $(x_3)_{f_6}$Electromechanical Expulsive | | 3 |
| $f_7$: Actuate Primary Control Surfaces | $(x_1)_{f_7}$Hydraulic Actuator (HA) | $(x_2)_{f_7}$Electro Hydrostatic Actuator (EHA) | $(x_3)_{f_7}$Electro Mechanical Actuator (EMA) | | 3 |
| $f_8$: Actuate Secondary Control Surfaces | $(x_1)_{f_8}$Hydraulic Actuator (HA) | $(x_2)_{f_8}$Electro Hydrostatic Actuator (EHA) | $(x_3)_{f_8}$Electro Mechanical Actuator (EMA) | | 3 |
| $f_9$: Provide Electric Power | $(x_1)_{f_9}$Integrated Drive Generator (IDG) | $(x_2)_{f_9}$115V VF AC Starter/Generator | $(x_3)_{f_9}$230V VF AC Starter/Generator | | 3 |
| $f_{10}$: Provide Hydraulic Power | $(x_1)_{f_{10}}$Double Redundant (3000psi) | $(x_2)_{f_{10}}$Double Redundant (5000psi) | $(x_3)_{f_{10}}$Triple Redundant (3000psi) | $(x_4)_{f_{10}}$Triple Redundant (5000psi) | 4 |
| $f_{11}$: Provide Pneumatic Power | $(x_1)_{f_{11}}$Pressurized Bleed-Air | | | | 1 |

Figure 4.4: Notional morphological matrix for the application case-study

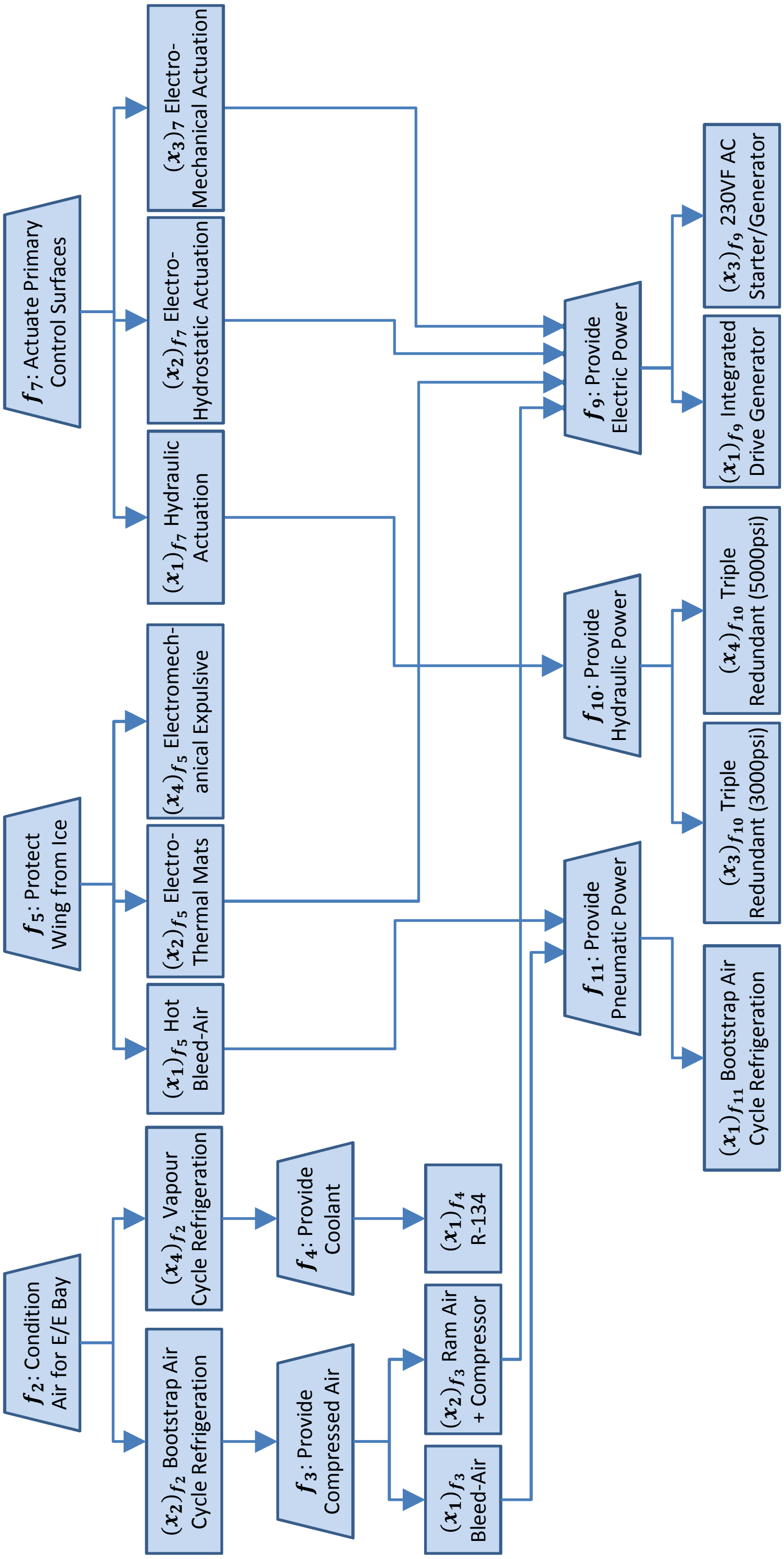


Figure 4.5: Notional function-means tree for the application case-study

(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 notional morphological matrix and function-means tree, a set of four systems architectures SA is generated for the application case-study, as shown in Table 4.9. In conventional systems architecture (Arc. 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 all-electric systems architecture (Arc. 4), only one power provider system (EPS) provides power to all power consumer systems. In other words, all the consumer systems are operated by electrical power. The more-electric architectures (Arc. 2 and Arc.3) are in between conventional and all-electric architectures, where Arc. 2 replaces pneumatic with electrical power, and Arc. 3 replaces hydraulic with electrical power. As mentioned earlier that although all-electric systems architectures are expected to be most efficient, the passenger aircraft manufacturers have preferred to take a conservative approach. Instead of all-electric, more-electric systems architectures are used to gradually move towards all-electric architectures (due to the technological or financial risks involved). 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.

|  | Power Provider |  |  | Power Consumer |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| SA | PPS | HPS | EPS | ECS | IPS | FCS | FS | LGS | Misc. |
| Arc. 1 | Yes | Yes | Yes | PPS | PPS | HPS | EPS | HPS | EPS |
| Arc. 2 | No | Yes | Yes | EPS | EPS | HPS | EPS | HPS | EPS |
| Arc. 3 | Yes | No | Yes | PPS | PPS | EPS | EPS | EPS | EPS |
| Arc. 4 | No | No | Yes | EPS | EPS | EPS | EPS | EPS | EPS |

Table 4.9: Set of Systems Architectures

After generation, the systems architectures set SA is analysed to evaluate architecture's impact parameters which include mass, power off-take (pneumatic and shaft power), ram drag, and costs. The impact parameters of the systems architectures are obtained by aggregating the impact parameters of the individual systems. For instance, Table 4.10 shows the impact parameters (mass and power off-take) of the two systems architectures (Arc. 1 and Arc. 2). The total mass of Arc. 1 is

21735.9lb, whereas the mass of Arc. 2 is 22110.8lb which is slightly more than Arc. 1. The conventional systems architecture (Arc. 1) requires 2.15kg/s pneumatic power and 159.4kW shaft power, whereas Arc. 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 (Arc. 2) is higher compared to conventional architecture (Arc. 1), the efficiency of Arc. 2 will be higher because the pneumatic power has far more severe impact on Specific Fuel Consumption (SFC).

|  | Arc. 1 |  | Arc. 2 |  |
|---|---|---|---|---|
| Systems | Mass | Power Off-take | Mass | Power Off-take |
| ECS | 1571.2lb | 1.05kg/s | 1713.8lb | 203.7kW |
| IPS | 201.3lb | 1.10kg/s | 208.4 | 49.9kW |
| FCS | 2821.3lb | 44.1kW | 2821.3lb | 44.1kW |
| FS | 710.4lb | 12.8kW | 710.4lb | 12.8kW |
| LGS | 8507.3lb | 24.3kW | 8732.5lb | 24.3kW |
| Misc. | 7924.4lb | 78.2kW | 7924.4lb | 78.2kW |
| Total | 21735.9lb | 2.15kg/s<br>159.4kW | 22110.8lb | 0kg/s<br>253.6kW |

TABLE 4.10: Systems Architectures Impact Parameters

In Table 4.10, the Misc. systems include galley, in-flight entertainment, avionics, and lightings, which are operated by electrical power.

#### 4.3.2.4 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. Tables 4.11 and 4.12 list the major components sets and systems architectures set for the application case-study, which were obtained in the previous steps.

| j | Major Components Sets ($MC_j$) | $q_j$ |
|---|---|---|
| 1 | Wings: $\{w_1, w_2, w_3 \ldots, w_{40}\}$ | 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 4.11: Sets of Major Components

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

TABLE 4.12: Set of Systems Architectures

The elements in the set of aircraft $A = \{a_1, a_2, \ldots, a_{n_a}\}$ are the individual aircraft which are obtained by applying the Cartesian operator (see Equation 3.13) 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 Equation 3.14. As shown below, the total number of aircraft $n_a$ that can be generated for the application case-study is 13440.

$$n_a = |A| = n_{sa} \prod_{j=1}^{n_{mc}} q_j = n_{sa} \cdot q_1 \cdot q_2 \cdot q_3 \cdot q_4 \cdot q_5 \cdot q_6 = (4)(40)(7)(1)(1)(6)(2) = 13440$$

After synthesis, the set of aircraft A can be analysed by evaluating the performance parameters through computational models. Figure 4.6 shows a screen shot of the AirCADia software, displaying the performance parameters of the aircraft set A in parallel coordinates plot. The later allows to visualise 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 Figure 4.6, each polyline represents an aircraft from the aircraft set A. Furthermore, the AirCADia software allows the

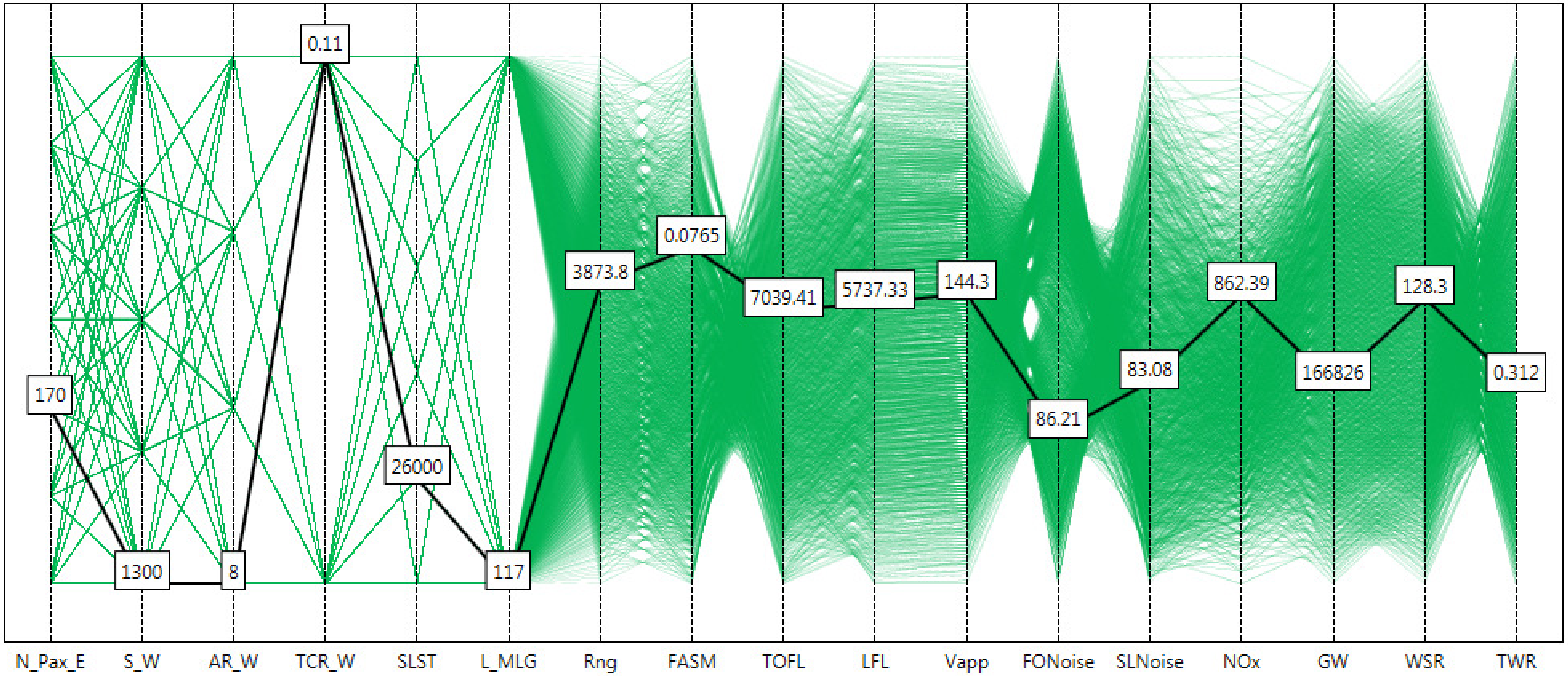


Figure 4.6: Set of Aircraft

designers 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 Figure 4.6. The performance parameters of the set of aircraft A can also be visualised as points in 2D scatter plots, as shown in Figure 4.7, where the two performance parameters, i.e. gross weight (GW) and range (Rng), are displayed. In addition, Figure 4.7 categorises the set of aircraft A into four groups, corresponding to the four systems architectures. The aircraft with systems architectures $sa_1$, $sa_2$, $sa_3$, and $sa_4$ are represented by points with red, green, blue, and purple colours, respectively.

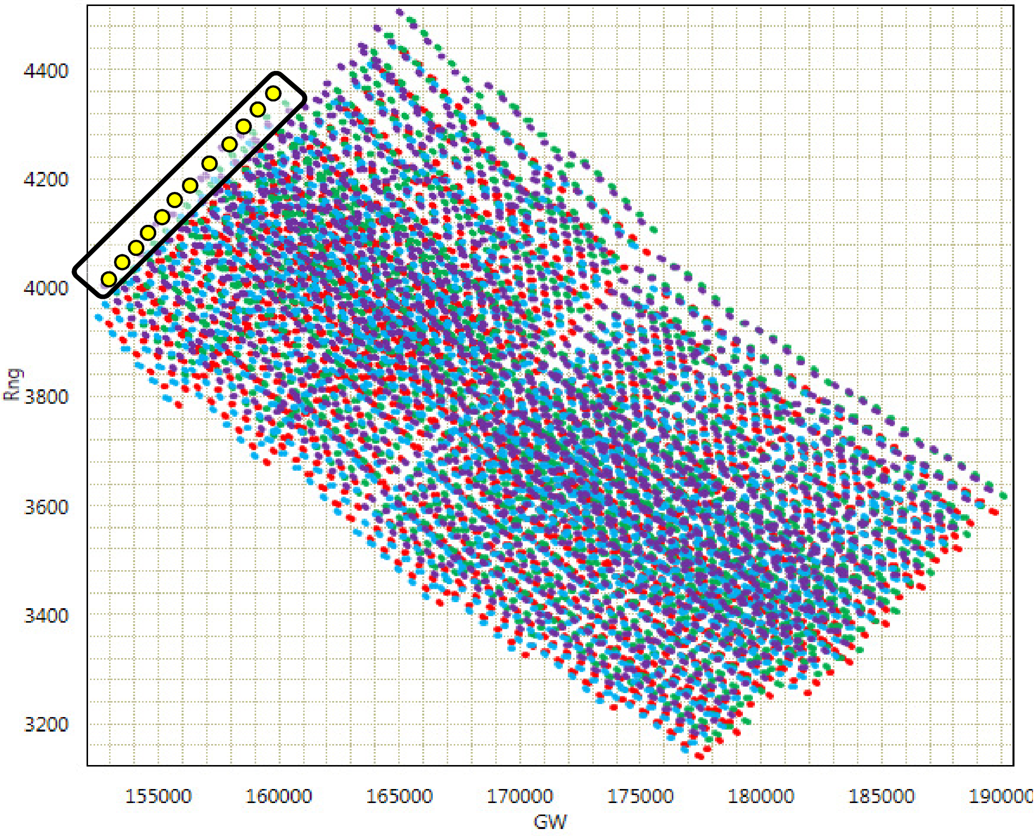


FIGURE 4.7: Set of Aircraft (Gross Weight vs Range)

In Figure 4.7, the black rounded rectangle encloses the aircraft solutions which are non-dominated or best (aka Pareto solutions) with respect to the gross weight (GW) and range (Rng). It is important to note that the best aircraft solutions with respect to the GW and Rng, which are represented by the yellow points in Figure 4.7, may not be the best with respect to the other performance parameters. For instance, the same aircraft set A is also visualised in Figures 4.8 and 4.9, where Figure 4.8 shows the mission performance parameters, i.e. Take-Off Field Length (TOFL) and Fuel per Available Seat Mile (FASM), whereas Figure 4.9 shows

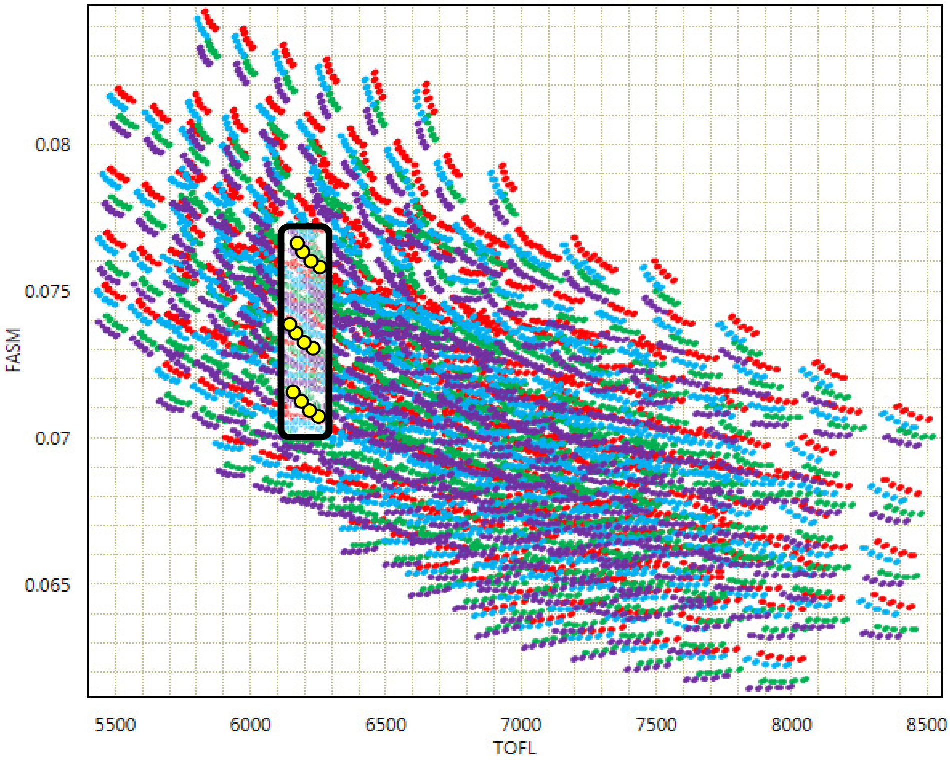


FIGURE 4.8: Set of Aircraft (Take-off Field Length vs Fuel Burned per Available Seat Mile)

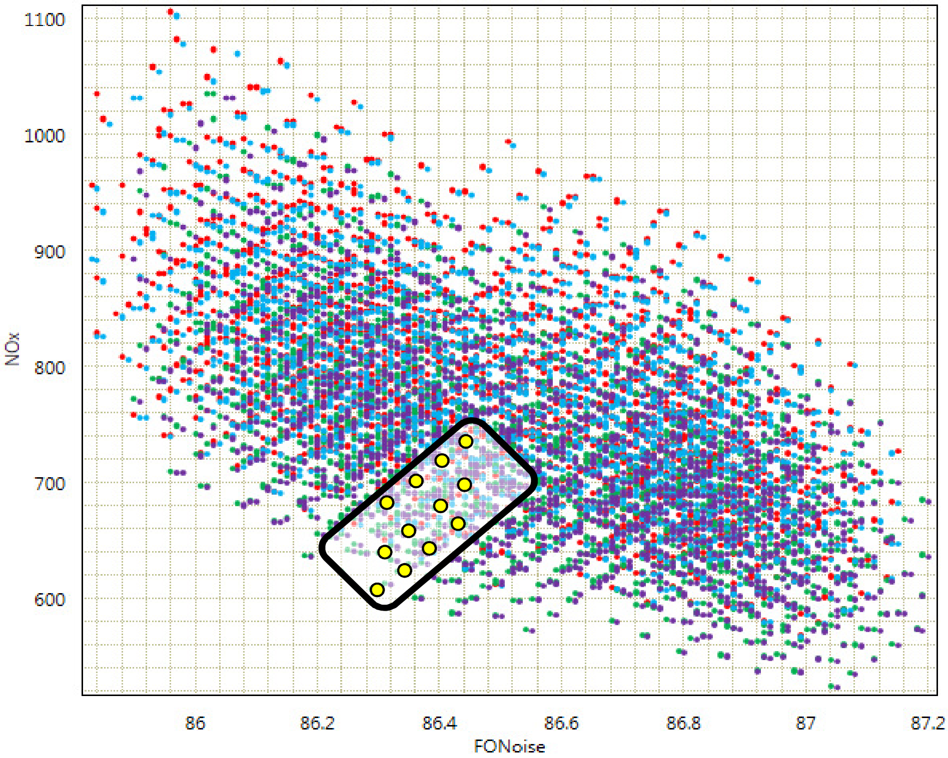


FIGURE 4.9: Set of Aircraft (Fly-Over Noise vs Nitrogen Oxides Emissions)

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 (in Figure 4.7) are also highlighted as yellow points in Figures 4.8 and 4.9. It can be seen from Figures 4.8 and 4.9 that the highlighted yellow aircraft solutions are not the Pareto solutions with respect to the TOFL, FASM, FONoise, and NOx. Multi-Criteria Decision Making (MCDM) algorithms can be employed to filter the Pareto solutions with respect to multiple performance parameters, which will be explained in Section 4.3.3.

A subset of the aircraft set A for the fixed number of passengers (N_Pax), sea-level static thrust (SLST), and main landing gear length (L_MLG) is shown in Figure 4.10. Here, N_Pax is equal to 210, SLST is equal to 30000lbm, and L_MLG is equal to 120in. It can be clearly seen that the all-electric systems architecture $sa_4$ (represented by the purple points) provides the best fuel efficiency, i.e. minimum fuel consumed per available seat mile FASM. The second best fuel efficiency is provided by the more-electric systems architecture $sa_2$ (represented by the green points), where the bleed-air Environmental Control System (ECS) and Ice Protection System (IPS) were replaced with the electrical technologies. Next, in the ranking for minimum fuel burned, is the more-electric architecture

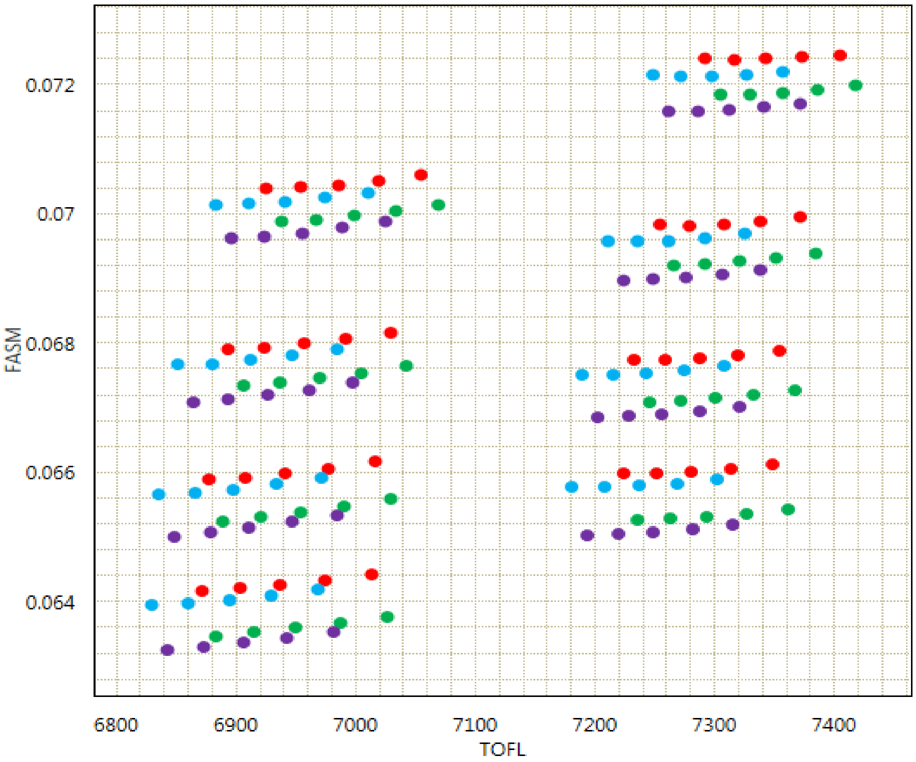


FIGURE 4.10: Effects of Systems Architectures on Performance Parameters

$sa_3$ (represented by the blue points), where the hydraulic power (for actuation) was replaced with the electrical power. The results indicate that the replacement of the pneumatic power (bleed-air) with the electrical power provides more benefit (i.e. less fuel burned) compared to the replacement of hydraulic power. The conventional systems architecture $sa_1$ (represented by the red points) provides the worst fuel efficiency compared to the other three (more/all-electric) systems architectures. Although the more/all-electric systems architectures provide better fuel efficiencies, other factors, e.g. low Technology Readiness Level (TRL), thermal and installation issues, may force the designers to choose conventional (fuel inefficient) systems architectures.

One of the expected advantage of the proposed methodology (and the Set-Based Design approach in general) is that it enables the designers to understand the design space before making critical design decisions. For instance, Figure 4.11 shows a screen shot of the AirCADia software, where multiple 2D scatter plots are linked to each other. By clicking on the points in design space, the designers can visualise the effects on performance space through the series of arrows. The top two plots show the wing design space, whereas the bottom plot shows the performance space. The objective is to determine the effects of the wing design parameters (reference area, aspect ratio, and thickness-to-chord ratio) on the performance parameters, therefore, the results are shown for only one systems architecture (conventional architecture $sa_1$ in this case) so that the plots are less-cluttered. The green arrows show that increasing the wing reference area (S_W) reduces the take-off field length (TOFL), whereas the effect of increasing the S_W is almost negligible for the fuel burned per available seat mile (FASM). On the other hand, the effect of increasing the wing aspect ratio (AR_W), represented by the blue arrows, is significant for TOFL and especially for FASM. Similarly, the purple arrows show that the effect of increasing the wing thickness-to-chord ratio (TCR_W) has detrimental effect on both the TOFL and FASM. In summary, the higher values for the reference area (S_W) and aspect ratio (AR_W), and the lower value for the thickness-to-chord ratio provide better performance for the take-off field length (TOFL) and fuel burned per available seat mile (FASM). This approach can be extended to determine the effects of any arbitrary number of design parameters on the performance parameters. Obtaining such information is quite valuable in making better decisions, specially for innovative concepts when past experience or knowledge is unavailable.

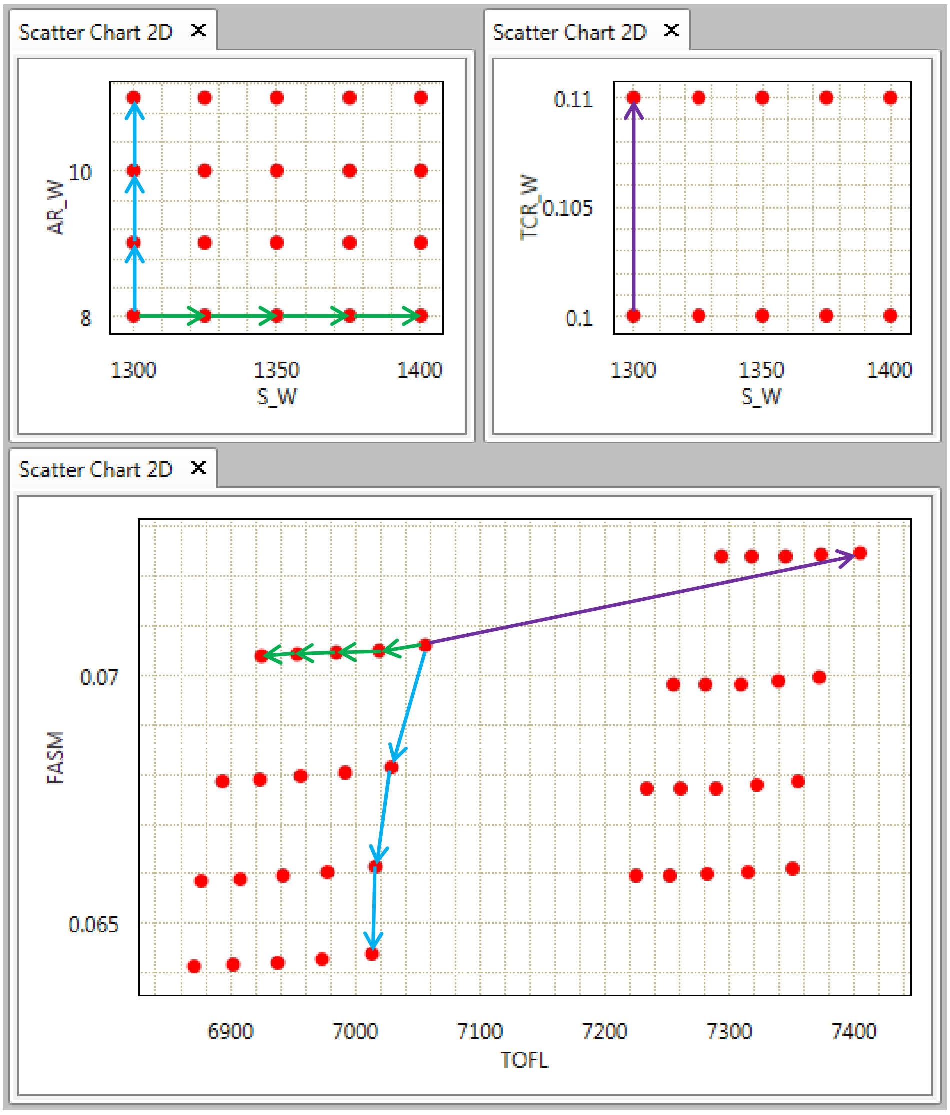


FIGURE 4.11: Effects of Design Variables Sets on Performance Parameters

#### 4.3.2.5 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 Figure 4.6) into aircraft family variants sets $A_k, \forall k = 1, n_{fv}$. For the application case-study, 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. Equation (3.16), is used to classify the set of aircraft A. As discussed in Chapter 3, the designer chooses which major components will be common or exclusive among the aircraft family variants. The passenger aircraft family design problem involves trade-off between components commonality and the performances of the individual aircraft family members. For the application case-study, as listed in Table 4.13, the 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.

| j | Major Components | Common/Exclusive |
|---|---|---|
| 1 | Wing | Common |
| 2 | Fuselages | Exclusive |
| 3 | Horizontal Tail | Common |
| 4 | Vertical Tail | Common |
| 5 | Engine | Exclusive |
| 6 | Landing Gear | Common |

Table 4.13: Common and Exclusive Major Components

After choosing the common and exclusive major components among the aircraft family variants, the design variables sets belonging to the exclusive major components are categorised. Table 4.8 shows the list of major components sets and their belonging design variables sets. As the fuselage and the engines are considered exclusive for the application case-study, therefore, 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 4.14. Hence, the number of common design variables sets $n_{CV}$ is 4, whereas the number of exclusive design variables sets $n_{SV}$ is 2. For the application case-study, 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 for the classification.

| Design Variable | Short | Baseline | Long |
|---|---|---|---|
| N_Pax | $\{150, 160\}$ | $\{170, 180\}$ | $\{190, 200, 210\}$ |
| S_W | $\{1300.0, 1325.0, 1350.0, 1375.0, 1400.0\}$ | | |
| AR_W | $\{8.0, 9.0, 10.0, 11.0\}$ | | |
| TCR_W | $\{0.10, 0.11\}$ | | |
| SLST | $\{25000.0, 26000.0\}$ | $\{27000.0, 28000.0\}$ | $\{29000.0, 30000.0\}$ |
| L_MLG | $\{117.0, 120.0\}$ | | |

Table 4.14: Common and Exclusive Discretised Design Variables Sets

Figure 4.12 illustrates the classification procedure for the application case-study, 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 discretised 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 Figure 4.12). The classification of the design variables sets results in 4 combinations for 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 not considered for the generation of aircraft families in the next step.

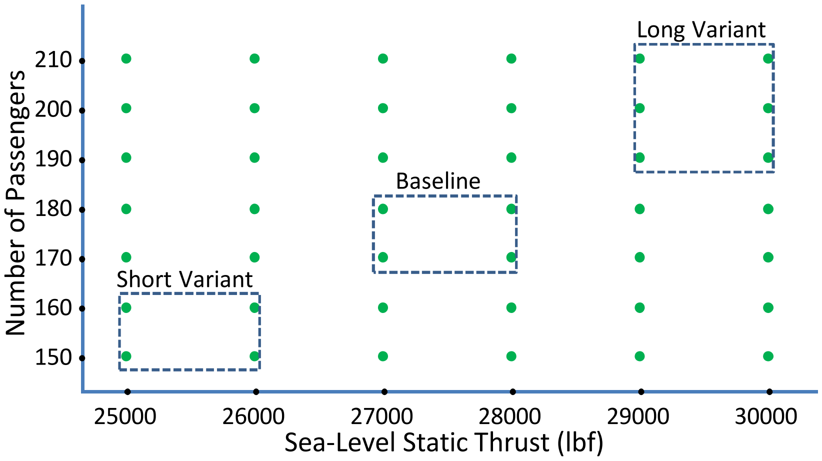


FIGURE 4.12: Aircraft Set Classification (Gross Weight vs Range)

Equation 3.16 can be used to determine the total number of aircraft for the three aircraft variants sets. For the application case-study, the total number of aircraft in the short, baseline, and long variants sets are 320, 320, and 480, respectively. Therefore, the total number of aircraft in all the three variants sets is reduced down to $320 + 320 + 480 = 1120$ from 13440 in the previous step. Figure 4.13 shows a screen shot of the AirCADia software, where the three aircraft family variants sets $\mathrm{A_S}$, $\mathrm{A_B}$, and $\mathrm{A_L}$ (obtained from classification) are displayed in a parallel coordinates plot. The red, green, and blue polylines represent the short, baseline, and long variants, respectively. Furthermore, the classified aircraft variants sets are also visualised in 2D scatter plots. Figures 4.14, 4.15, and 4.16 display the set of aircraft family variants, where Figure 4.14 shows the gross weight (GW) and range (Rng), Figure 4.15 shows the take-off field length (TOFL) and fuel burned per available seat mile (FASM), and Figure 4.16 shows the fly-over noise (FONoise) and nitrogen oxides (NOx) emissions. In Figures 4.14, 4.15, and 4.16, the red,

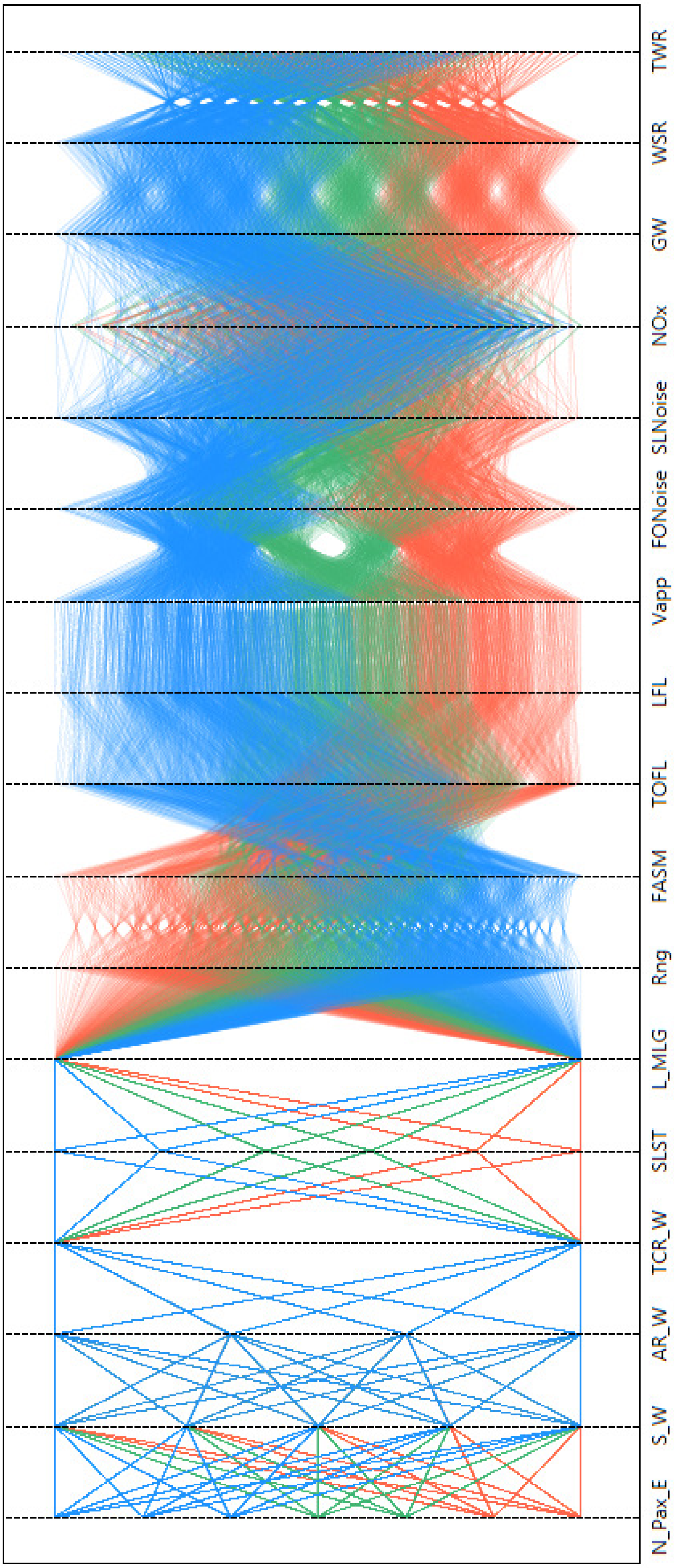


Figure 4.13: Three Sets of Aircraft Family Variants

green, and blue points represent the set of short, baseline, and long variants, respectively.

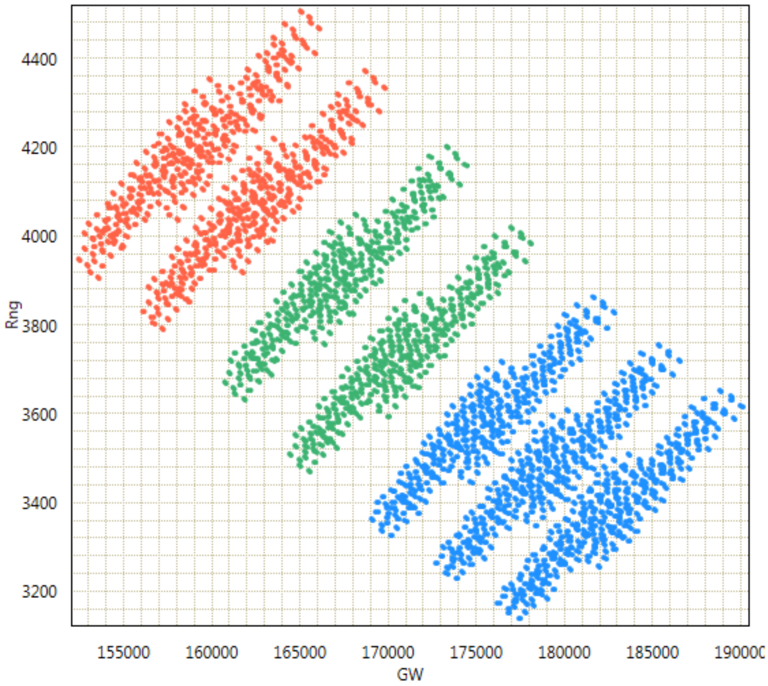


Figure 4.14: Aircraft Set Classification (GW vs Rng)

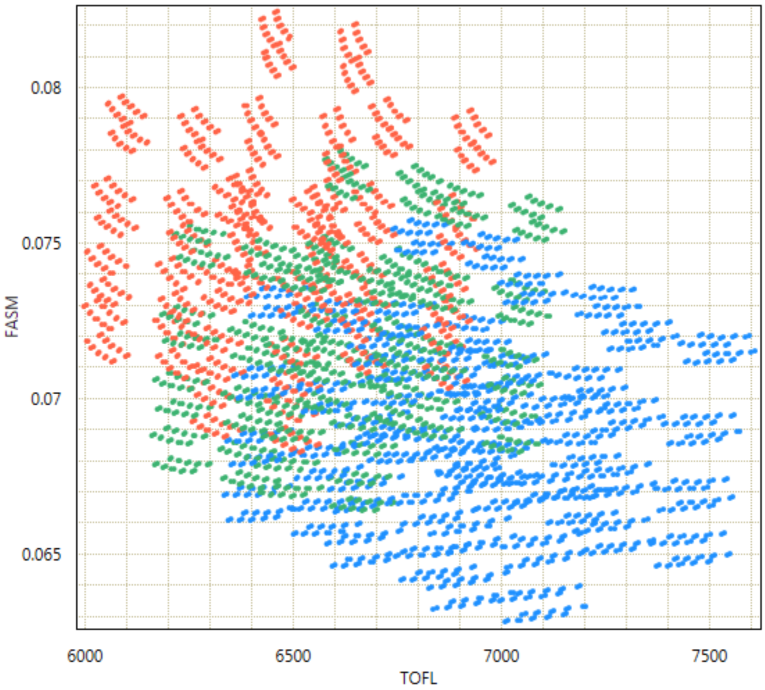


Figure 4.15: Aircraft Set Classification (TOFL vs FASM)

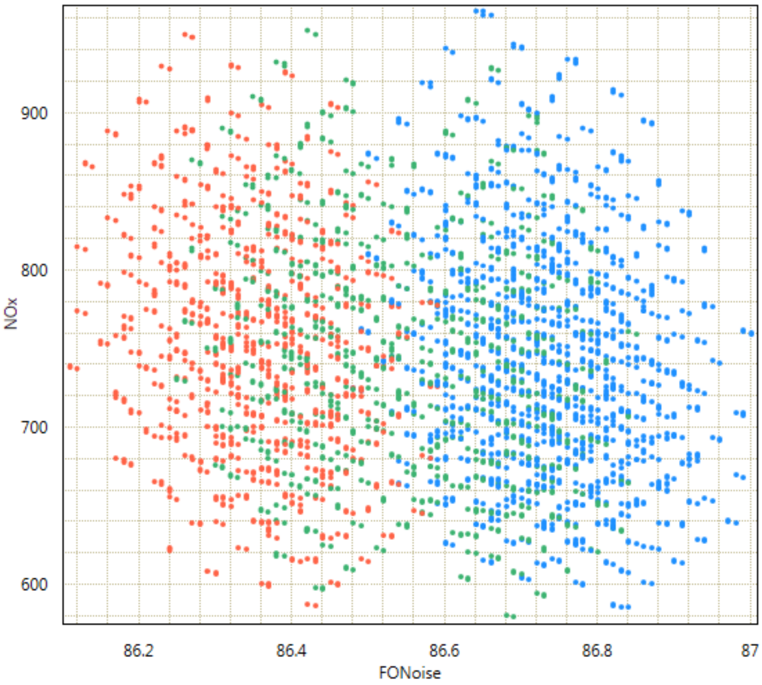


Figure 4.16: Aircraft Set Classification (FONoise vs NOx)

#### 4.3.2.6 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. For the application case-study, 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 Equation 3.17), is applied on the three aircraft family variants sets (i.e. $A_S$, $A_B$, and $A_L$ shown in Figure 4.13) to generate the aircraft family set AF.

It was mentioned in Chapter 3 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 (i.e. for the largest family member). This means that smaller aircraft variants tend to have over-sized systems' components. For instance, if the maximum electrical power required by the systems of short, baseline, and long variants are 160HP, 180HP, and 200HP, respectively, then the electrical generators are sized for 200HP (maximum required value) so that the same electrical generator can satisfy the electrical power requirements for all the aircraft family variants. Development of aircraft families (by using common systems architecture and components among all the family members) degrades the individual performance, but saves research, development, testing and evaluation (RDT&E) costs. When components are shared among multiple aircraft, the RDTE cost is also shared among all the family members. However, an additional cost is associated with developing components for use on multiple aircraft. Table 4.15 lists the additional factors [5] for the RDT&E cost of the shared components. For example, if a component is shared by two aircraft, then the total engineering cost is 20% higher than if the component had only been developed for a single aircraft. Similarly, the total RDT&E cost of a shared component is 17.615% higher than if the component had only been developed for a single aircraft.

| Engineering | Manufacturing | Tooling | Fabrication | Support | Average |
|---|---|---|---|---|---|
| 20.0% | 50.0% | 5.0% | 5.0% | 50.0% | 17.615% |

Table 4.15: RDT&E Cost Factor for Common Components [5]

After generating the set of aircraft family AF, the analysis at this step involves estimating the updated performance parameters for each of the variants by considering common systems' components. Furthermore, the acquisition cost is evaluated which is composed of the RDT&E and manufacturing costs. Table 4.16 shows the effects of using common systems between three family members on the aircraft level performance parameters and the family acquisition cost. Columns 2 to 4 list the systems masses and the aircraft level performance parameters (including acquisition cost) for the case when exclusive system components are used, i.e. the systems components are sized for the individual aircraft members. On the other hand, columns 5 to 7 list the systems masses and the aircraft level performance parameters (including acquisition cost) for the case when common system components are used, i.e. the systems components are sized for the largest aircraft family member. The highlighted rows in Table 4.16 show that these systems are shared but could have been sized exclusively for the aircraft family member. It can be seen that the systems for smaller family members are over-sized, e.g. the mass of environmental control system (M_ECS) for the short variant of the aircraft family is 1699lbm. However, if the system is not shared (i.e. sized separately for the short variant), then the mass of the environmental control system (M_ECS) is 1484lbm.

The use of common systems degrades all the performance parameters, e.g. the range (Rng) of the short variant is reduced from 4052nm to 4040nm. Although the use of common components degrades the performance parameters, the overall acquisition cost of the family (Fam_Cost) is reduced from 241.27M$ to 235.70M$.

| | Exclusive Systems | | | Shared Systems | | |
|---|---|---|---|---|---|---|
| Param. | Short | Baseline | Long | Short | Baseline | Long |
| N_Pax | 160 | 180 | 210 | 160 | 180 | 210 |
| SLST | 26000.0 | 28000.0 | 30000.0 | 26000.0 | 28000.0 | 30000.0 |
| M_W | 17049 | 17049 | 17049 | 17049 | 17049 | 17049 |
| M_F | 17351 | 18503 | 20231 | 17351 | 18503 | 20231 |
| M_HT | 1420 | 1420 | 1420 | 1420 | 1420 | 1420 |
| M_VT | 953 | 953 | 953 | 953 | 953 | 953 |
| M_ECS | 1484 | 1571 | 1699 | 1699 | 1699 | 1699 |
| M_FS | 696 | 696 | 696 | 696 | 696 | 696 |
| M_FCS | 2757 | 2757 | 2757 | 2757 | 2757 | 2757 |
| M_IPS | 205 | 205 | 205 | 205 | 205 | 205 |
| M_HPS | 824 | 927 | 1145 | 916 | 1030 | 1145 |
| M_PPS | 129 | 145 | 179 | 143 | 161 | 179 |
| M_EPS | 1521 | 1711 | 2112 | 1690 | 1901 | 2112 |
| Sft_Pow | 171 | 184 | 202 | 171 | 184 | 202 |
| Bld_Air | 3.16 | 3.32 | 3.57 | 3.16 | 3.32 | 3.57 |
| TOFL | 6577 | 6736 | 7321 | 6613 | 6767 | 7321 |
| LFL | 5548 | 5750 | 6095 | 5560 | 5761 | 6095 |
| Vapp | 140 | 144 | 150 | 141 | 145 | 150 |
| GW | 161887 | 169960 | 183732 | 162362 | 170382 | 183732 |
| Rng | 4052 | 3726 | 3340 | 4040 | 3716 | 3340 |
| FASM | 0.0734 | 0.0709 | 0.0678 | 0.0736 | 0.0711 | 0.0678 |
| FONoise | 86.31 | 86.57 | 86.65 | 86.30 | 86.56 | 86.65 |
| SLNoise | 82.80 | 83.03 | 83.53 | 82.85 | 83.06 | 83.53 |
| NOx | 765 | 753 | 754 | 766 | 754 | 754 |
| Fam_Cost | 241.27 | | | 235.70 | | |

Table 4.16: Effects of Common Systems Architecture and Components on the Aircraft-Level Performance Parameters

Equation 3.18 can be used to determine the total number of aircraft families $n_{af}$ that can be generated in the aircraft family sets AF. In the previous step, the design variables sets were divided into two categories: common and exclusive, depending on the designers choice for common and exclusive major components. The exclusive design variables sets, i.e. the number of passengers (N_Pax) and sea-level static thrust (SLST), were then classified into three sets, corresponding to the aircraft family variants, as shown in Table 4.14. Tables 4.17 and 4.18 show the common and exclusive discretised design variables sets and their cardinalities that can be used to determine the total number of aircraft families for the application case-study.

| i | Var. | 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 |

TABLE 4.17: Common Discretised Design Variables Sets

| i | Var. | Short k = 1 | $p_{i1}$ | Baseline k = 2 | $p_{i2}$ | Long k = 3 | $p_{i3}$ |
|---|---|---|---|---|---|---|---|
| 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 4.18: Exclusive Discretised Design Variables Sets

The total number of aircraft families $n_{af}$ that can be generated for the application case-study 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.

$$\begin{aligned}
n_{af} &= n_{sa} \cdot \prod_{i=1}^{n_{cv}} p_i \cdot \prod_{i=1}^{n_{ev}} \prod_{k=1}^{n_{fv}} p_{ik} \\
&= n_{sa} \cdot \prod_{i=1}^{4} p_i \cdot \prod_{i=1}^{2} \prod_{k=1}^{3} p_{ik} \\
&= n_{sa} \cdot p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot \left(p_{11} \cdot p_{12} \cdot p_{13}\right) \cdot \left(p_{21} \cdot p_{22} \cdot p_{23}\right) \\
&= 4 \cdot 5 \cdot 4 \cdot 2 \cdot 2 \cdot \left(2 \cdot 2 \cdot 3\right) \cdot \left(2 \cdot 2 \cdot 2\right) \\
&= 30720
\end{aligned}$$

Figure 4.17 shows a screen shot of the AirCADia software, displaying the performance parameters of the aircraft family set AF in the parallel coordinates plot, where a single polyline represents an aircraft family of three members. The numbers 1, 2, and 3 at the end of the parameters names represent the long, baseline, and short variants, respectively. For example, the parameters names N_Pax_E1, N_Pax_E2, and N_Pax_E3 represent the number of passengers for economy class for the long, baseline, and short variants, respectively. Figure 4.18 displays the set of aircraft families in 2D scatter plots.

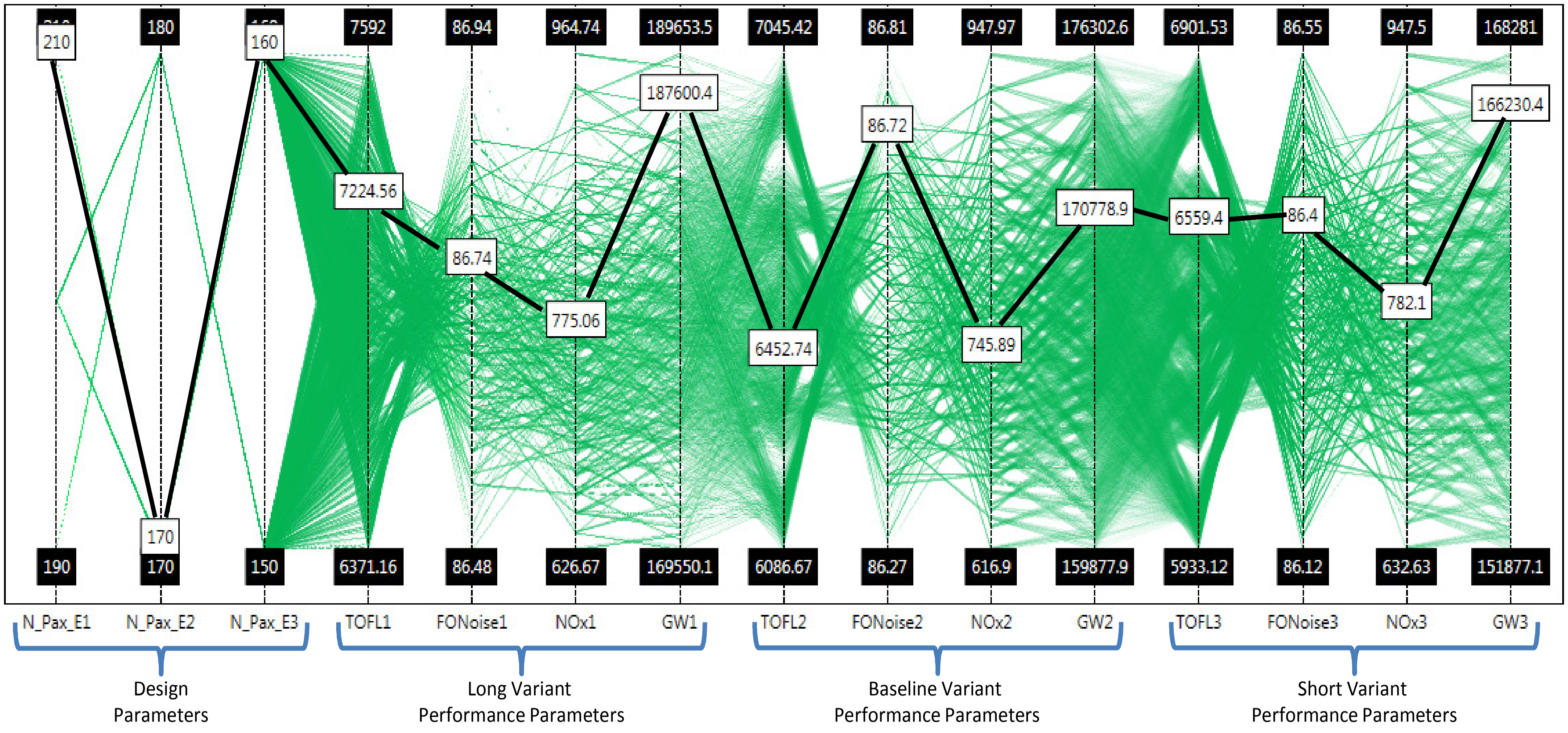


FIGURE 4.17: Aircraft Family Set

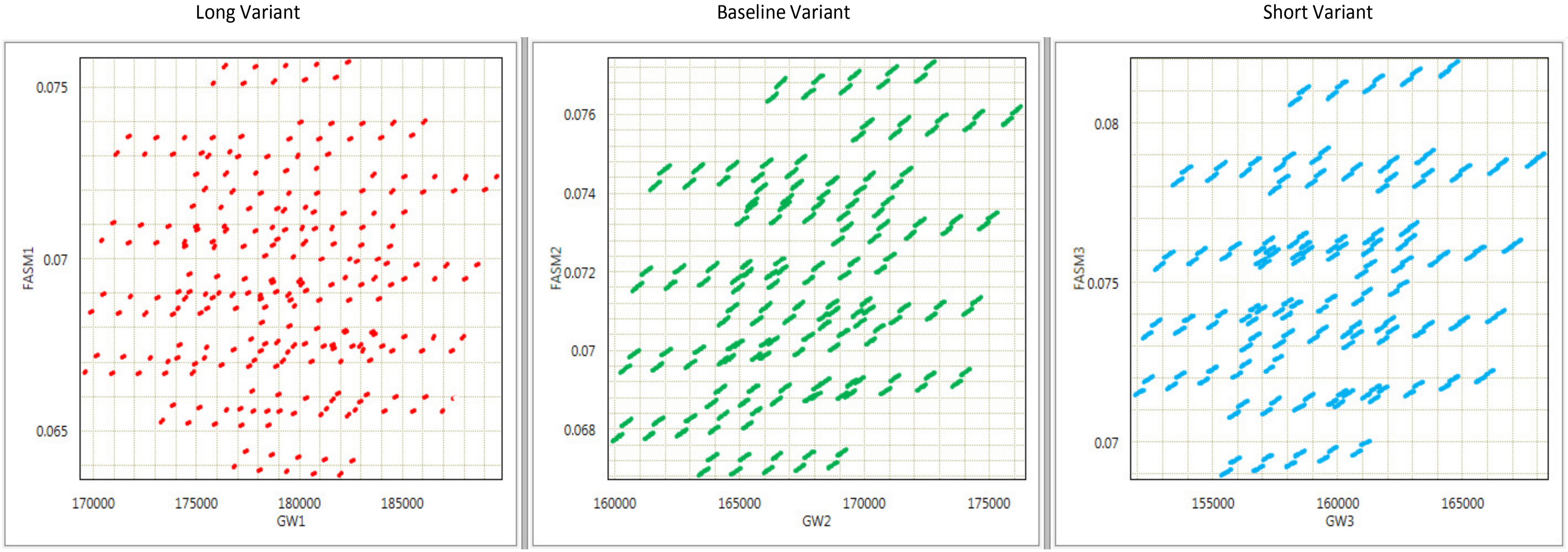


Figure 4.18: Aircraft Family Set [Gross Weight (GW) vs Fuel Burned per Available Seat Mile (FASM)]

### 4.3.3 Narrowing-Down Phase

After the synthesis and analysis of the set of aircraft families, the third phase is the down-selection phase where infeasible and inferior aircraft family solutions are progressively discarded. Figure 4.19 shows the design variables sets for the application case-study, which were used to generate the set of aircraft families in Phase 2. The total number of aircraft families that were generated with these design variables sets is 30720. The objective of this phase is to reduce or shrink these design variables sets gradually as more design knowledge is gained.

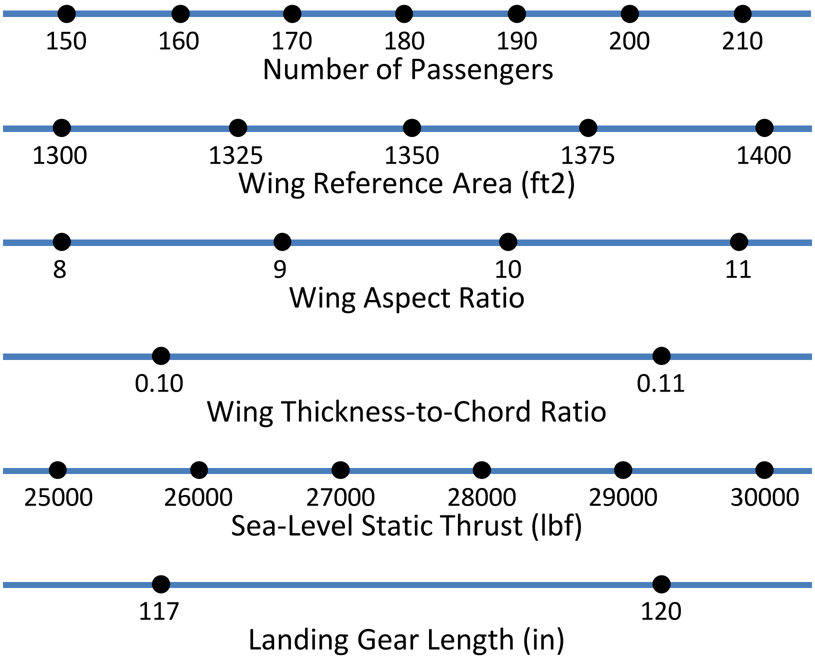


FIGURE 4.19: Discretised Design Variables Set

#### 4.3.3.1 Step 8: Down-Selection through Constraint Satisfaction

In this step, constraint satisfaction is applied in order to down-select the feasible aircraft family solutions. Apart from the performance constraints defined in Step 1, other constraints (e.g. compatibility) are used in this step to discard infeasible aircraft family solutions. Table 4.2 lists the performance constraints considered for the current application case-study. The proposed methodology enables the designers to change the constraints limiting values without performing any sizing and evaluation, which is in contrast with the traditional optimisation-based (point-based) approaches which require new problem formulation (and sizing/evaluation) if the constraints limiting values are changed.

For the application case-study, 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 designers may choose other values depending on the market requirements. If the number of passengers requirement change during the design process, the designers would be able to change the constraint value without performing new sizing and evaluation studies. The side-views of the three aircraft family variants with the selected number of passengers (N_Pax) in shown in Figure 4.20. The design variable set for landing gear length has two options (see Figure 4.19). In Figure 4.20, the lower values of the landing gear length, i.e. 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 12 degrees for the long aircraft variant, as shown in Figure 4.20. In addition, it does not provide enough room for the higher bypass ratio engines due to insufficient clearance distance. Therefore, for the application case-study, the set of landing gear length (L_MLG) was reduced to only one value i.e. 120in. Furthermore, in order to provide higher thrust-to-weight ratio and meet

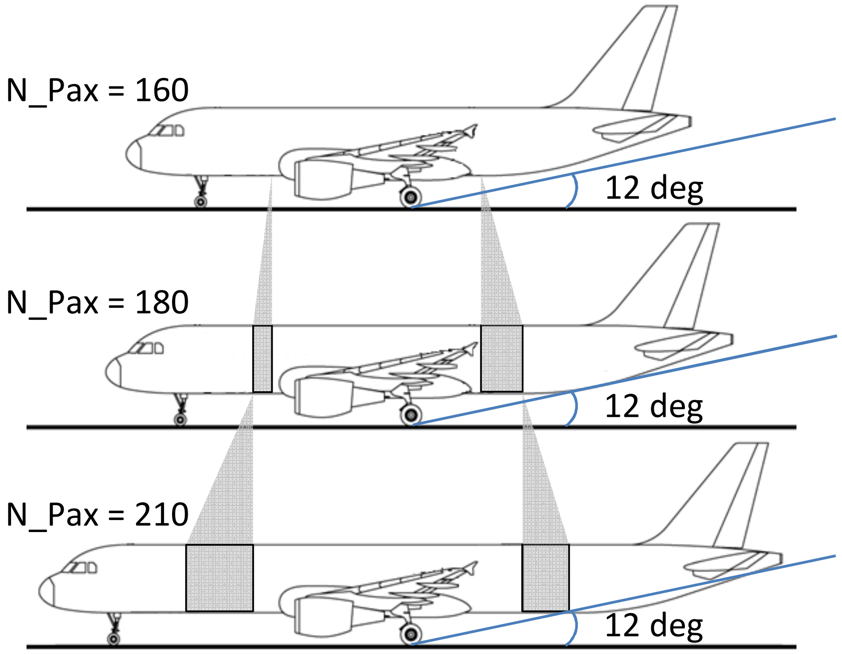


Figure 4.20: Discretised Design Variables Set

the top-of-the-climb thrust requirements, the higher values for the sea-level static thrust (SLST) is used for all the aircraft variants, i.e. 26000, 28000, and 30000 for the short, baseline, and long variants, respectively.

A method for feasibility analysis using iso-contours for constraints (described in Section 3.5.1 is used here which allows the designers to gain insight into the topology of the feasible regions within the design space and to narrow-down the design sets by discarding infeasible regions. Figure 4.21 shows the feasible regions of the baseline aircraft variants for the four architectures. The different feasible regions

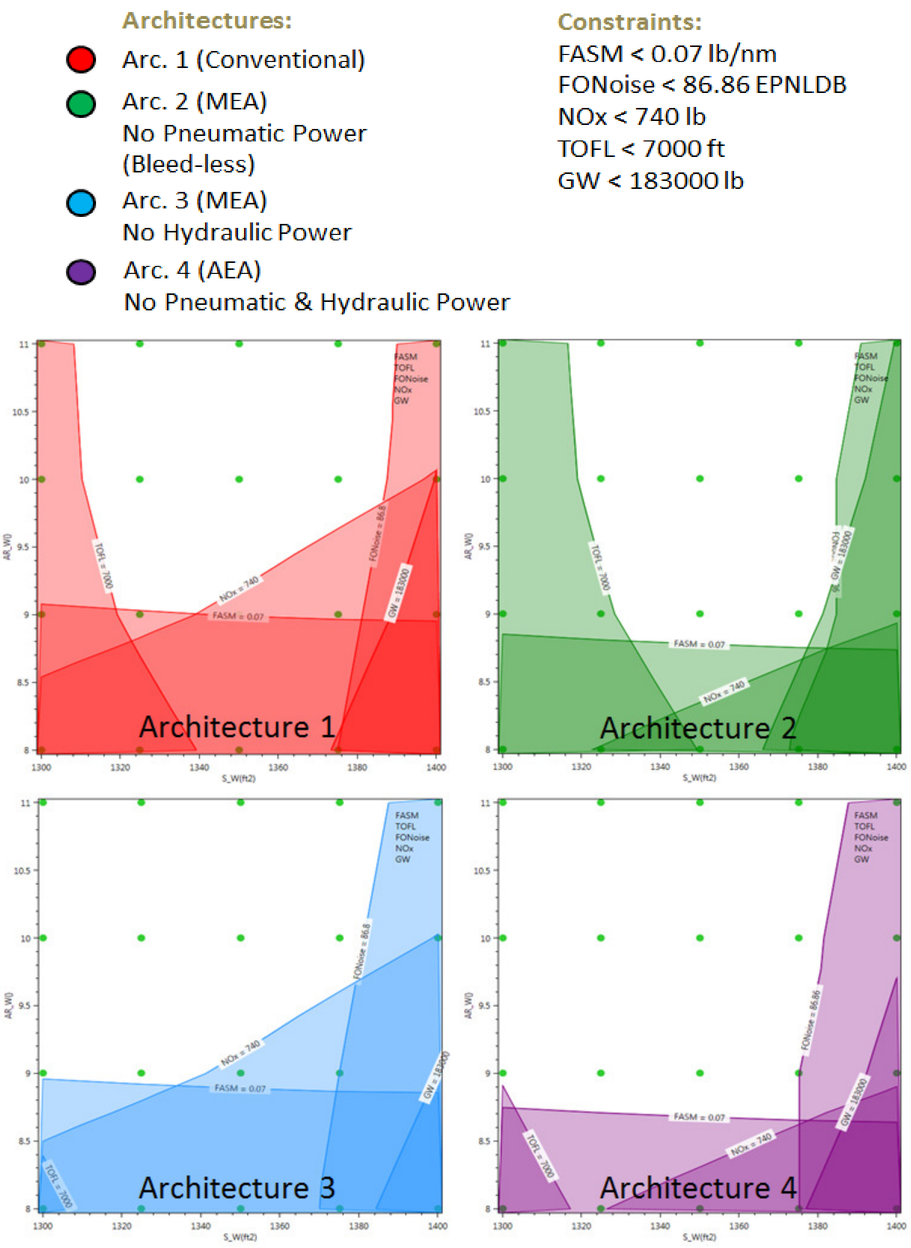


FIGURE 4.21: Constraints Satisfaction (Baseline Systems Architectures)

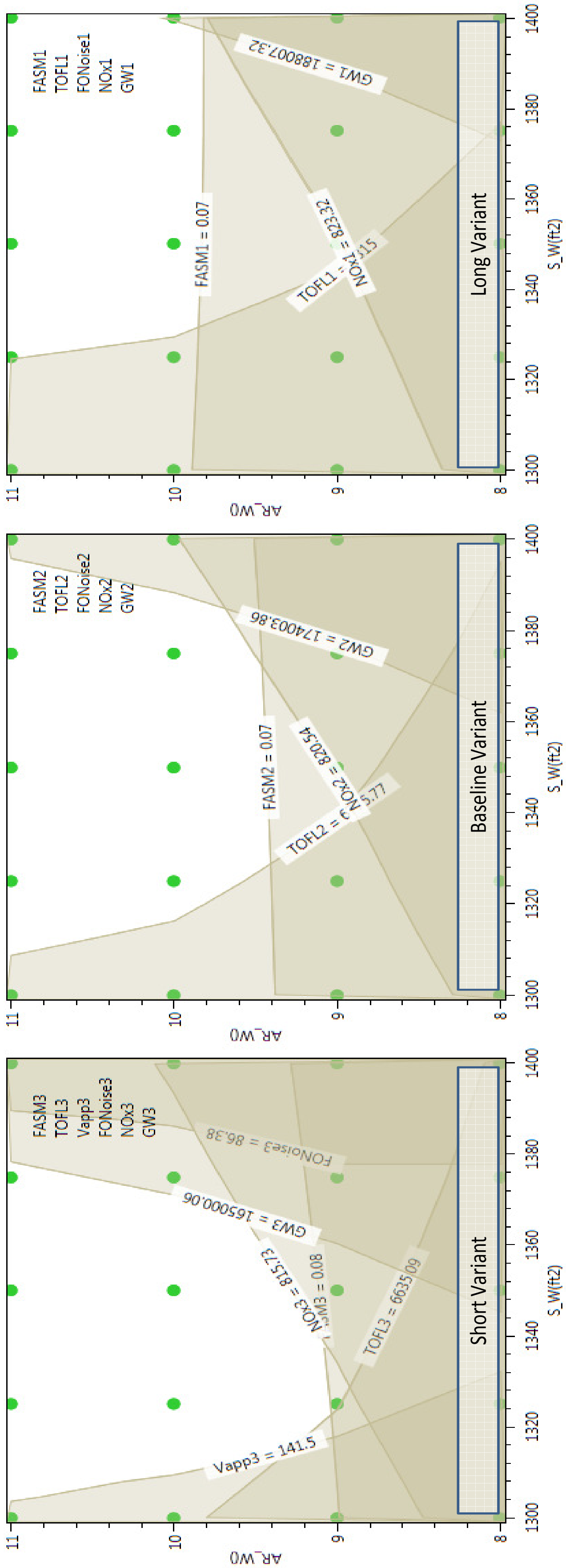


Figure 4.22: Constraints Satisfaction (Conventional Systems Architecture $sa_1$)

are due to the different performance efficiencies of the architectures.

Figure 4.22 shows a screen shot of the AirCADia software, where the set reduction for two design variables sets, i.e. wing area (S_W) and aspect ratio (AR_W), is performed for the conventional systems architecture by using the performance constraints from Table 4.2.

Since it was decided to utilise the same wing among all the variants of the aircraft family, the design variables sets for wing area, aspect ratio, and thickness-to-chord ratio are intersected and reduced in order to satisfy the requirements for all the three aircraft variants. Whereas, it was decided to utilise the different engine among the family variants, the reduced design variable set for sea-level static thrust is different for the three variants. For common design variables, the reduced design variables sets for all the family members are then intersected to determine the common design variables sets that satisfy all the requirements for all family members. Figure 4.23 shows the set reduction process for wing area and aspect ratio by performing intersection between design variable sets for the three members of the aircraft family. The intersected blue region represents the feasible region with respect to all the family variants requirements.

It is important to note that if the requirements change during the design process, the constraints iso-contours can be interactively moved by the designers in real-time to identify new feasible aircraft family solutions or region without formulating and executing any new studies.

Similarly, the feasible regions for the other systems architectures can be obtained. Figure 4.24 shows the constraints iso-contours of the three aircraft family variants for the two systems architectures. The top-row shows the feasible regions for conventional systems architecture $\mathrm{sa}_1$, whereeas the bottom-row shows the feasible regions for the more-electric bleed-less systems architecture $\mathrm{sa}_2$. The bleed-less systems architecture is heavier compared to the conventional architecture, therefore the take-off filed length (TOFL) and gross weight (GW) constraints constrict the feasible region. However, the fuel burned per available seat mile (FASM) and nitrogen oxide (NOx) emissions constraints move away from the feasible region, i.e make the feasible region bigger. Similarly, the intersection region for the other systems architectures were determined. Figure 4.25 shows the intersection (blue) region of more-electric systems architecture $\mathrm{sa}_2$ for the three variants of the aircraft family. Although the feasible region is smaller compared to the conventional

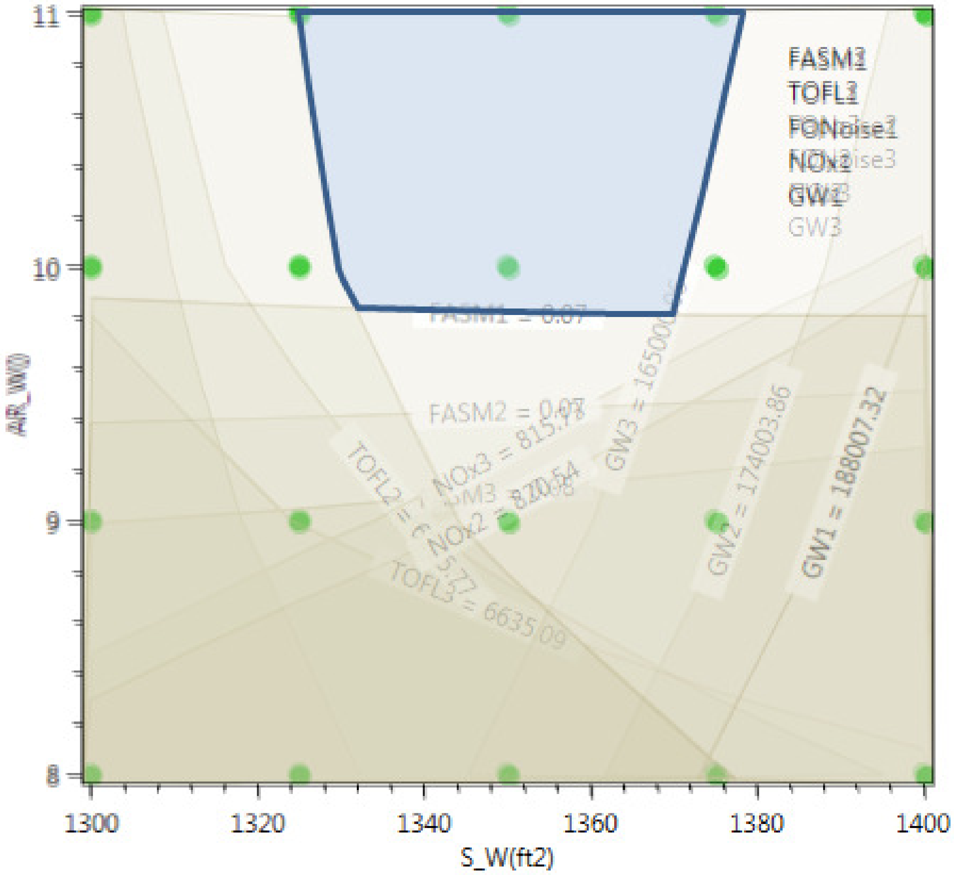


Figure 4.23: Set Intersection for Conventional Systems Architecture

systems architecture (shown in Figure 4.23), it is fuel efficient, i.e. consumes less fuel per available seat mile.

Figure 4.26 shows the intersection region of the two systems architectures, i.e. $sa_1$ and $sa_2$. The feasible intersected region between two systems architectures (represented by the red region) is robust to both systems architectures. In other words, if the wing design is selected from the red region, the decision to choose the systems architectures can be delayed because the selected wing design would result in a feasible design no matter which architecture is selected.

With the proposed methodology, the designers are free to down-select any of the aircraft family solutions synthesised and analysed in phase 2. For instance, in addition to the performance constraints, the designers may apply other qualitative criteria (compatibility constraints), such as ease of assembly and the extent of available space for inserting other components, as needed. This freedom is significant because some of these constraints cannot be modelled in the computational mathematical models.

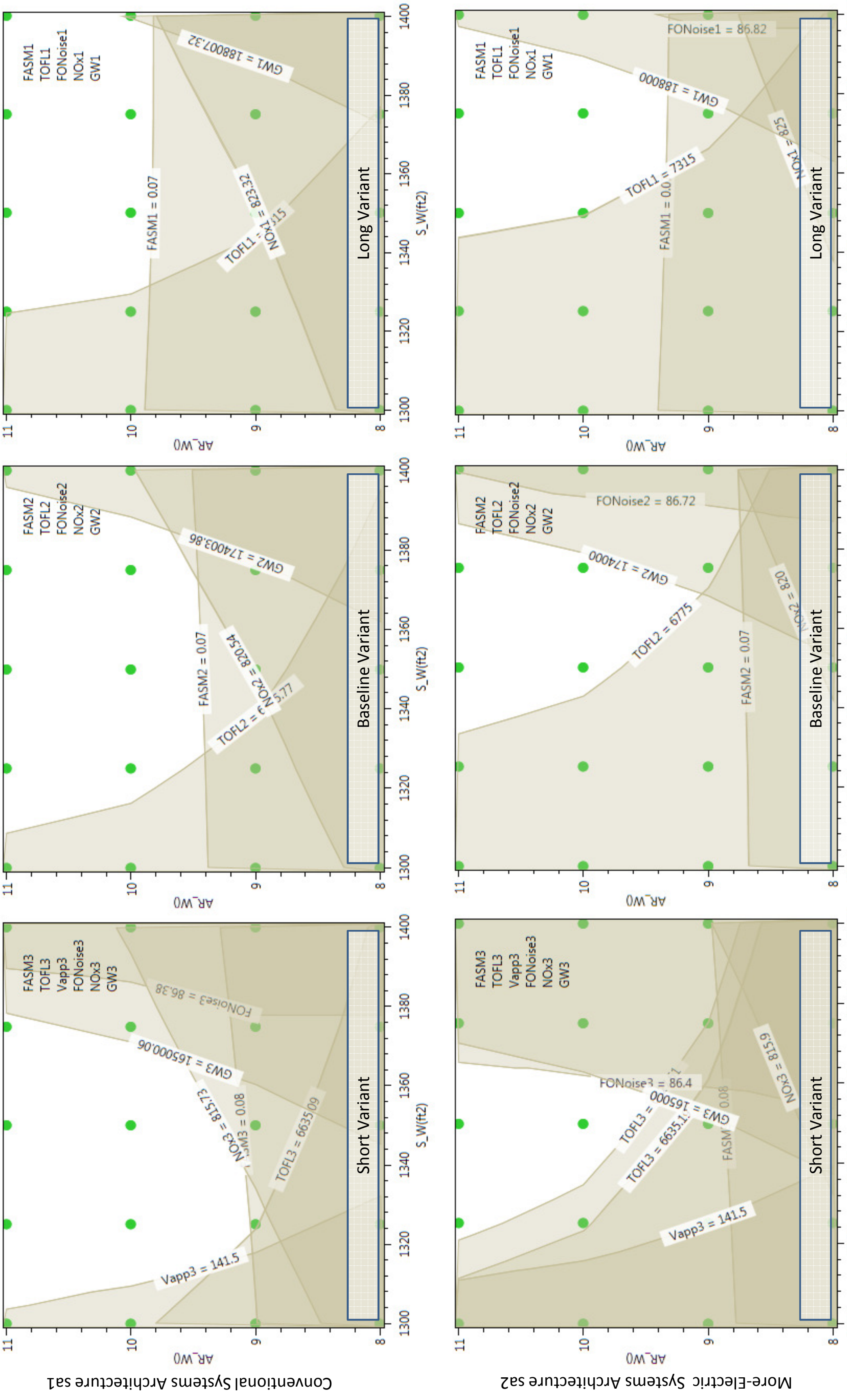


Figure 4.24: Constraints Satisfaction (Top-Row: Conventional Systems Architecture sa$_1$, Bottom-Row: More-Electric Systems Architecture sa$_2$)

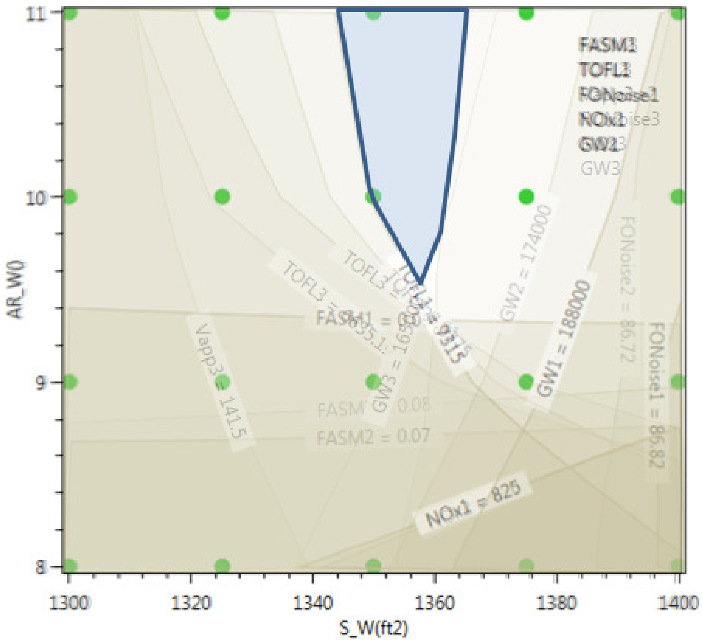


Figure 4.25: Set Intersection for More-Electric (Bleed-less) Systems Architecture

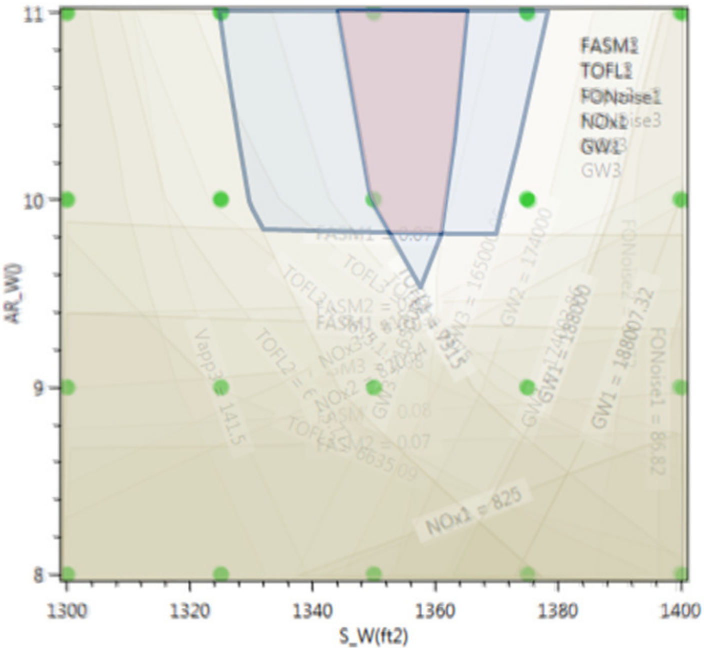


Figure 4.26: Set Intersection between Systems Architectures $sa_1$ and $sa_2$

#### 4.3.3.2 Step 9: Down-Selection through Ranking

After applying the constraints on the aircraft family set, the reduced design variable sets are further narrowed down by constricting the intersected design space by utilising a non-dominated filtering or by tightening the constraints and/or introducing further constraints arising from other domains such as manufacturing, maintenance and so forth. As discussed in Chapter 3, a multicriteria decision making method, named Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) [131] is employed to rank the remaining feasible aircraft family solutions. TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. It compares a set of alternatives by identifying weights for each criterion, normalising scores for each criterion and calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion. The weights of the parameters or criteria can be taken from Table 4.2 which were obtained by using the house of quality (HoQ).

After using the constraints satisfaction to down-select the feasible solutions, the reduced sets of design variables are shown in Figure 4.27. The red points represent the rejected options. Out of the remaining aircraft family solutions, TOPSIS can be used to rank the feasible solutions.

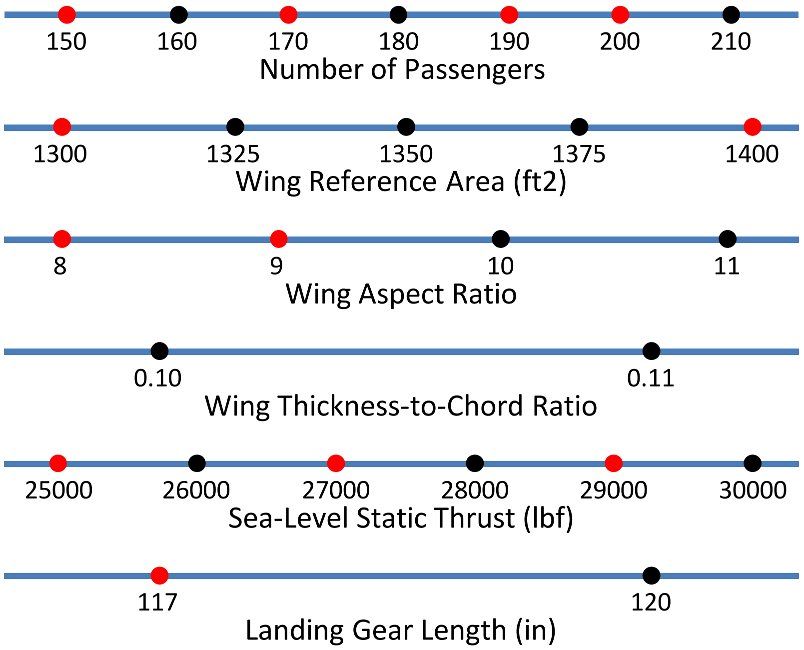


FIGURE 4.27: Reduced Design Variables Sets

Figure 4.18 shows the performance parameters of the three aircraft family variants in separate 2D scatter plots. It is difficult to compare two aircraft families with these plots. A combined metric is, therefore, developed to evaluate and rank the aircraft families. The proposed metric is the addition of all the normalised weighted performance parameters of each aircraft family variant. Here, $\mathrm{PE_{fam}}$ represent the collective performance efficiency of the aircraft family, $\mathrm{Q_k}$ represents the quantity of the kth family member, $\mathrm{n_{pp}}$ represent the number of performance parameters considered for evaluating the performance efficiency of the aircraft family, $\mathrm{w_i}$ represents the associated weight of the performance parameter, and $\mathrm{PP_i'}$ represents the normalised performance parameter value.

$$\mathrm{PE_{fam}} = \sum_{\mathrm{k=1}}^{\mathrm{n_{fv}}} \frac{\mathrm{Q_k}}{\sum_{\mathrm{k=1}}^{\mathrm{n_{fv}}} \mathrm{Q_k}} \prod_{\mathrm{i=1}}^{\mathrm{n_{pp}}} \mathrm{w_i} \cdot \mathrm{PP_i'}$$

For the application case-study, five performance parameters are considered for evaluating the performance efficiency of the aircraft families. These parameters include gross weight (GW), fuel burned per available seat mile (FASM), take-off field length (TOFL), flyover noise (FONoise), and nitrogen oxides emissions (NOx). The corresponding arbitrarily selected weights of the performance parameters are 1/6, 2/6, 1/6, 1/6, and 1/6. Therefore, the performance efficiency of the aircraft family can be evaluated as:

$$\begin{aligned}\mathrm{PE_{fam}} =& \frac{\mathrm{Q_S}}{\mathrm{Q_S + Q_B + Q_L}}\left(\frac{1}{6}\mathrm{GW_S'} \cdot \frac{2}{6}\mathrm{FASM_S'} \cdot \frac{1}{6}\mathrm{TOFL_S'} \cdot \frac{1}{6}\mathrm{FONoise_S'} \cdot \frac{1}{6}\mathrm{NOx_S'}\right) + \\ & \frac{\mathrm{Q_B}}{\mathrm{Q_S + Q_B + Q_L}}\left(\frac{1}{6}\mathrm{GW_B'} \cdot \frac{2}{6}\mathrm{FASM_B'} \cdot \frac{1}{6}\mathrm{TOFL_B'} \cdot \frac{1}{6}\mathrm{FONoise_B'} \cdot \frac{1}{6}\mathrm{NOx_B'}\right) + \\ & \frac{\mathrm{Q_L}}{\mathrm{Q_S + Q_B + Q_L}}\left(\frac{1}{6}\mathrm{GW_L'} \cdot \frac{2}{6}\mathrm{FASM_L'} \cdot \frac{1}{6}\mathrm{TOFL_L'} \cdot \frac{1}{6}\mathrm{FONoise_L'} \cdot \frac{1}{6}\mathrm{NOx_L'}\right)\end{aligned}$$

For the application case-study, it is assumed that the market need for the short, baseline, and long aircraft variants is 600, 900, and 900, respectively. Therefore, the performance efficiency of the aircraft family can be evaluated as:

$$\begin{aligned}\mathrm{PE_{fam}} =& \frac{600}{600 + 900 + 900}\left(\frac{1}{6}\mathrm{GW_S'} \cdot \frac{2}{6}\mathrm{FASM_S'} \cdot \frac{1}{6}\mathrm{TOFL_S'} \cdot \frac{1}{6}\mathrm{FONoise_S'} \cdot \frac{1}{6}\mathrm{NOx_S'}\right) + \\ & \frac{900}{600 + 900 + 900}\left(\frac{1}{6}\mathrm{GW_B'} \cdot \frac{2}{6}\mathrm{FASM_B'} \cdot \frac{1}{6}\mathrm{TOFL_B'} \cdot \frac{1}{6}\mathrm{FONoise_B'} \cdot \frac{1}{6}\mathrm{NOx_B'}\right) + \\ & \frac{900}{600 + 900 + 900}\left(\frac{1}{6}\mathrm{GW_L'} \cdot \frac{2}{6}\mathrm{FASM_L'} \cdot \frac{1}{6}\mathrm{TOFL_L'} \cdot \frac{1}{6}\mathrm{FONoise_L'} \cdot \frac{1}{6}\mathrm{NOx_L'}\right)\end{aligned}$$

Figure 4.28 shows the performance efficiency parameter $\mathrm{PE}_{\mathrm{fam}}$ of the set of aircraft families. The performance efficiency $\mathrm{PE}_{\mathrm{fam}}$ is plotted against the family acquisition cost. The evaluation of the $\mathrm{PE}_{\mathrm{fam}}$ parameter does not require any sizing/evaluation of aircraft performance parameters. In fact, if the importance of the requirements change, the designer may change the weights of the performance parameters to obtain the updated performance efficiency $\mathrm{PE}_{\mathrm{fam}}$ parameter.

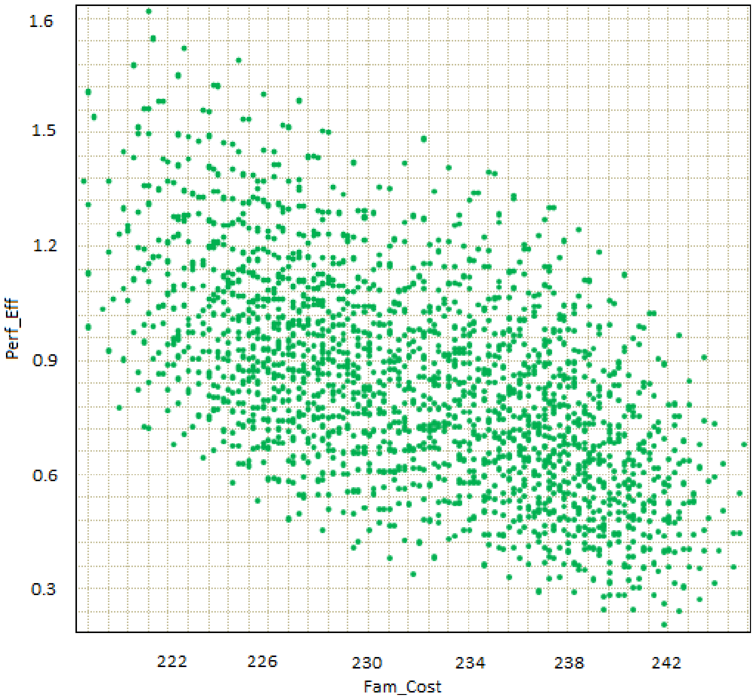


FIGURE 4.28: Aircraft Family Cost vs Efficiency

## 4.4 Summary

In this chapter, an application case-study was used to demonstrate the proposed methodology for designing passenger aircraft families. The objective of the application case-study was to highlight the capabilities of the proposed methodology, not to come up with the best design.

The proposed methodology is expected to enable a more systematic exploration of wider design spaces by identifying several feasible or satisfactory solutions, hence providing more freedom of choice for the designers. It allows parallel design and analysis of the major components and systems for multiple aircraft family solutions. Although it may appear that a lot of work needs to be performed at the start, it saves time by reducing the number of design changes or iterations required later. The proposed methodology provides 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 integrates the systems architectures analysis and design within the conceptual aircraft synthesis and design, allowing an instantaneous investigation of the impact of system architecture modifications on the aircraft and mission performance. Although the proposed methodology provides several benefits by considering multiple solutions, it requires extra upfront work to synthesise and analyse multiple solutions.

A method for constraint analysis using iso-contours is proposed for the down-selection of aircraft family set. The proposed method divides the multi-dimensional design space into multiple 2D projections (slices) that can be used to gain insight into the topology of the feasible design space. The proposed constraint analysis method does not require new evaluations of the computational models, instead the previously obtained results from the set generation are used by using interpolation in order to compute the constraints iso-contours. This makes the method well-suited for design space exploration at the early stage by enabling the designers to interactively move the iso-contours of the dormant and active constraints in real-time. Apart from determining the feasible design space for down-selection, the constraint iso-contours offer the flexibility to perform a sensitivity analysis of the design variables towards different constraints, which enables to assess the relative importance of the design parameters. This helps the designers to gain knowledge and understand the design space, i.e. how (and in which direction) to open or expand the feasible design space by infusing different concepts and technologies. Furthermore, it allows the designers to obtain the optimal design space graphically.

# Chapter 5

# Evaluation

## 5.1 Introduction

This chapter is concerned with the evaluation of the proposed methodology for designing passenger aircraft families, 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 Chapter 4) was executed by using the PBD approach. Next, the application case-study and the two approaches (proposed methodology and the traditional PBD approach) along with their results 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.

The rest of this chapter is divided into three sections. Section 5.2 describes the results and the issues faced when the traditional PBD approach was applied to the application case-study. Section 5.3 provides the feedback obtained from the industrial experts and finally Section 5.4 presents the summary and conclusions.

## 5.2 Traditional PBD Approach Implementation

As mentioned earlier, the traditional point-based design PBD approach employs sequential, optimisation-based methods where a single design concept is selected quite early in the design phase (after brainstorming or utilising past experience), which is then subsequently tweaked or modified until it satisfies all the requirements.

For the traditional PBD approach implementation, the same computational sizing models (i.e. Flight Optimization System (FLOPS) and the developed mathematical models for non-conventional systems architectures) are used, as for the proposed methodology. Furthermore, the genetic algorithm (NSGAII) optimiser [132], available in the AirCADia software, is employed to obtain the results.

It was decided that all-electric systems architecture will be used for all the three variants of the aircraft family, due to the expected benefits of reduced mass and fuel burn by 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 the electric counterparts i.e. Electro Mechanical Actuators (EMAs) for FCS and LGS. Similarly, instead of using engine 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. Table 5.1 provides the optimisation problem formulation considered for designing the baseline aircraft variant. The purpose of implementing the traditional PBD approach is to compare it with the proposed methodology, therefore this chapter only demonstrates the design of baseline aircraft variant. The same procedure can be used to apply the traditional optimisation-based approach for the other two aircraft variants.

| Design Variables | Constraints | Objectives |
|---|---|---|
| SLST = [25000 – 30000] lbf<br>S_W = [1300 – 1400] $ft^2$<br>AR_W = [8 – 11]<br>TCR_W = [0.10 – 0.11]<br>BPR = [6 – 8] | Rng = 3000nm<br>TOFL $\leq$ 6725ft<br>SLNoise $\leq$ 85.0dB | Fuel [lbm] - minimise<br>MTOW [lbm] - minimise |

Table 5.1: Optimisation Formulation for PBD Implementation

After formulating and setting the optimisation problem, NSGAII genetic algorithm was used to obtain the results. The key parameters of the resulting baseline aircraft variant are shown in Table 5.2.

The rest of this section presents a hypothetical scenario when traditional point-based design PBD approach is applied.

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.10 | 29000 | 6.0 | 115.2 | 43320 | 42629 | 168901 | 6643 | 84.3 |

Table 5.2: Initial PBD Design

**Iteration 1:** The resulting design point for baseline variants (featuring high aspect ratio in order to achieve higher fuel efficiency and reduce airframe noise) satisfied all the constraints considered during the optimisation process. Later, during the analysis phase, it was pointed out that elimination of the hydraulic system may cause thermal issues with Electro Mechanical Actuators (EMAs), since the hydraulic fluid used in Hydraulic Power System (HPS) provides a convenient means of transporting and dissipating the heat generated by the actuation system. Initial calculations were performed which confirmed that natural radiation and convection is not sufficient to keep the EMAs at the acceptable operating temperature. It was, therefore, decided to install a dedicated thermal management system (Heat Pipes) for EMAs. In heat pipes, the thermal load conducts from the source through the evaporator cold plate and causes boiling of the working fluid within the evaporator body. The vapour flows through the flexible section to the condenser. The condenser is either mounted onto cooler structure such as the aircraft skin, or air-cooled through ram air. Heat pipes require no external power and the working fluid is fully contained so the device can be easily installed or removed. The heat pipe also has the advantage that it requires only a small temperature difference between the heat source and sink for effective operation. Heat pipes with aircraft skin mounted condensers (instead of using ram air) were used for thermal management of flight control actuators, which imposed additional mass of 105.2lbm. The sizing was conducted for the new mass, which resulted in a slight increment of block fuel and MTOW, as shown in Table 5.3 where the block fuel and MTOW have increased from 42629lbm to 42664lbm and 168901lbm to 169057lbm, respectively. The penalty for adding heat pipes was low, therefore all the constraints were still satisfied.

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.10 | 29000 | 6.0 | 115.2 | 43320 | 42664 | 169057 | 6653 | 84.4 |

Table 5.3: Iteration 1

**Iteration 2:** Although adding heat pipes solved the thermal issues with EMAs with small penalty on block fuel and MTOW, it was realised later on during the integration phase that the assembly of EMA and heat pipes was not fitting inside the wing profile for aileron EMA due to the required condenser geometry for heat pipes, as shown in Figure 5.1.

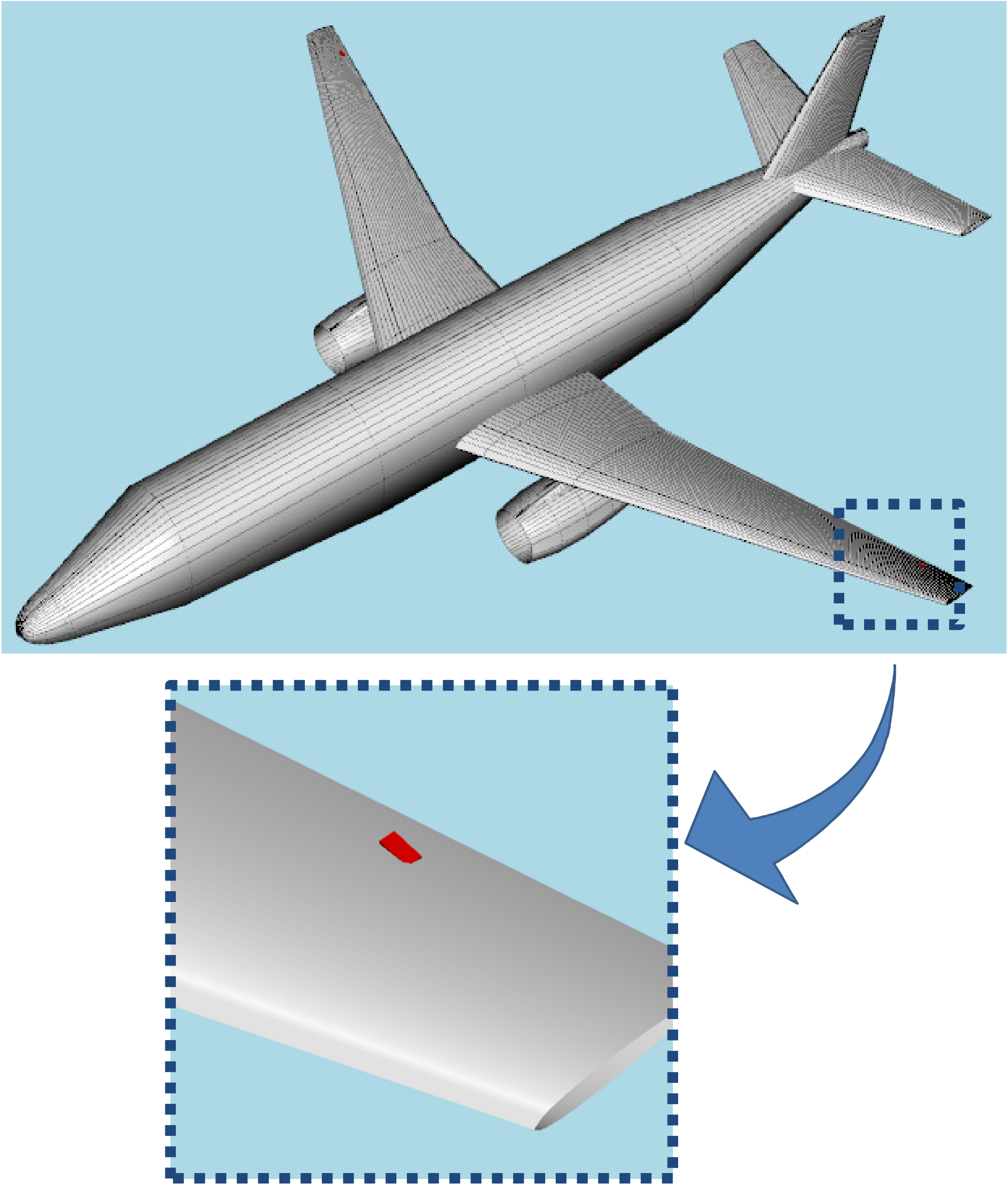


FIGURE 5.1: Assembly of EMA and Heat Pipe for Aileron

At this point, it was decided to consider switching back to hydraulic actuators. An assessment study was initiated and it was found that the design rework required to introduce HPS and switching EMAs to hydraulic actuators was 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 wing profile. The results of the new study (initiated by increased TCR_W) are shown in Table 5.4. The increment of TCR_W resulted in adverse effects on the block fuel and MTOW, where the block fuel and MTOW have increased from 42664lbm to 44093lbm and 169057lbm to 169923lbm, respectively.

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.11 | 29000 | 6.0 | 115.2 | 43320 | 44093 | 169923 | 6714 | 84.6 |

Table 5.4: Iteration 2

**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 42664lbm to 44093lbm. This resulted into another problem: the total fuel capacity of the fuel tanks 43220lbm turned out to be less than the fuel required 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 of the new study are shown in Table 5.5. The increment of the TCR_W and fuel tank capacity increased the MTOW from 169923lbm to 170138lbm.

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.11 | 29000 | 6.0 | 115.2 | 46000 | 44144 | 170138 | 6729 | 84.7 |

Table 5.5: Iteration 3

**Iteration 4:** Although increasing the fuel tank capacity solved the 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 Table 5.5, the resulting Take-Off Field Length (TOFL) was 6729ft which is higher than the constraint limiting value of 6725.0ft shown in Table 5.1. This problem was solved by initiating another study where the Sea-Level Static Thrust (SLST) was increased from 29000.0lbf to 30000.0lbf. The results of this new study are shown in Table 5.6 where the TOFL was decreased from 6729.0ft to 6560.0ft, hence satisfying the TOFL constraint. Because of increased thrust, the block fuel and MTOW have increased from 44144lbm to 44925lbm and 170138lbm to 170971lbm, respectively.

**Iteration 5:** Increasing the SLST solved the issue with TOFL constraint, but resulted in violation of the sideline noise constraint. As shown in Table 5.6, the

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.11 | 30000 | 6.0 | 115.2 | 46000 | 44925 | 170971 | 6560 | 85.6 |

Table 5.6: Iteration 4

resulting sideline noise was 85.6dB which is higher than the constraint limiting value of 85.0dB shown in Table 5.1. In order to reduce the combined sideline noise, it was decided 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 Table 5.7. The increment of BPR improved the fuel efficiency of the aircraft. The total fuel required to achieve a 3000nm was reduced from 44925 to 44256, which also resulted in MTOW decrement from 170971 to 170205.

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.11 | 30000 | 7.0 | 115.2 | 46000 | 44256 | 170205 | 6571 | 84.2 |

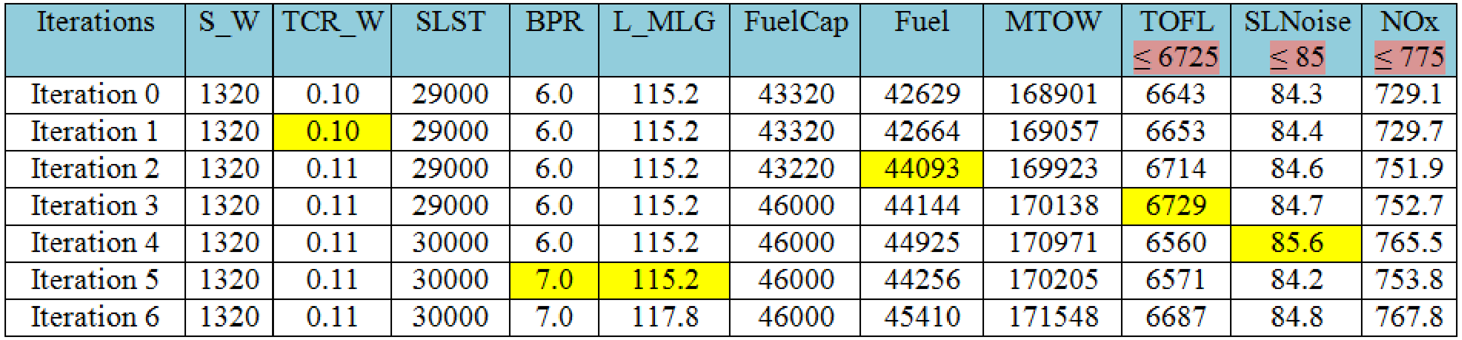
Table 5.7: Iteration 5

**Iteration 6:** Although increasing the BPR resolved the issue with sideline noise constraint, it was figured out later during the integration phase that the engine clearance distance is not sufficient due to the higher engine diameter resulting from increased BPR. In order to rectify this problem, another study was initiated where the landing gear length L_LG was increased from 115.2in to 117.8in. The results of this study are shown in Table 5.8. The increment of L_LG also increased the landing gear mass, and the resulting MTOW was increased from 170205lbm to 171548lbm. All the constraints were satisfied by this design, 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 42629lb to 45410lb (increment of 6.5%), and the MTOW was increased from 168901lbm to 171548lbm (increment of 1.6%).

| TCR_W | SLST | BPR | L_LG | F_Cap | Fuel | MTOW | TOFL | SLNoise |
|---|---|---|---|---|---|---|---|---|
| 0.11 | 30000 | 7.0 | 117.8 | 46000 | 45410 | 171548 | 6687 | 84.8 |

Table 5.8: Iteration 6

Figure 5.2 shows the overall design rework or iteration involved when traditional point-based design PBD approach was used to design baseline aircraft family variant with innovative all-electric systems architecture. Figure 5.3 shows the variations in MTOW, block fuel, and TOFL due to the design rework or iterations.



| Iterations | S_W | TCR_W | SLST | BPR | L_MLG | FuelCap | Fuel | MTOW | TOFL $\leq 6725$ | SLNoise $\leq 85$ | NOx $\leq 775$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Iteration 0 | 1320 | 0.10 | 29000 | 6.0 | 115.2 | 43320 | 42629 | 168901 | 6643 | 84.3 | 729.1 |
| Iteration 1 | 1320 | 0.10 | 29000 | 6.0 | 115.2 | 43320 | 42664 | 169057 | 6653 | 84.4 | 729.7 |
| Iteration 2 | 1320 | 0.11 | 29000 | 6.0 | 115.2 | 43220 | 44093 | 169923 | 6714 | 84.6 | 751.9 |
| Iteration 3 | 1320 | 0.11 | 29000 | 6.0 | 115.2 | 46000 | 44144 | 170138 | 6729 | 84.7 | 752.7 |
| Iteration 4 | 1320 | 0.11 | 30000 | 6.0 | 115.2 | 46000 | 44925 | 170971 | 6560 | 85.6 | 765.5 |
| Iteration 5 | 1320 | 0.11 | 30000 | 7.0 | 115.2 | 46000 | 44256 | 170205 | 6571 | 84.2 | 753.8 |
| Iteration 6 | 1320 | 0.11 | 30000 | 7.0 | 117.8 | 46000 | 45410 | 171548 | 6687 | 84.8 | 767.8 |

FIGURE 5.2: Design Iterations associated with PBD Approach

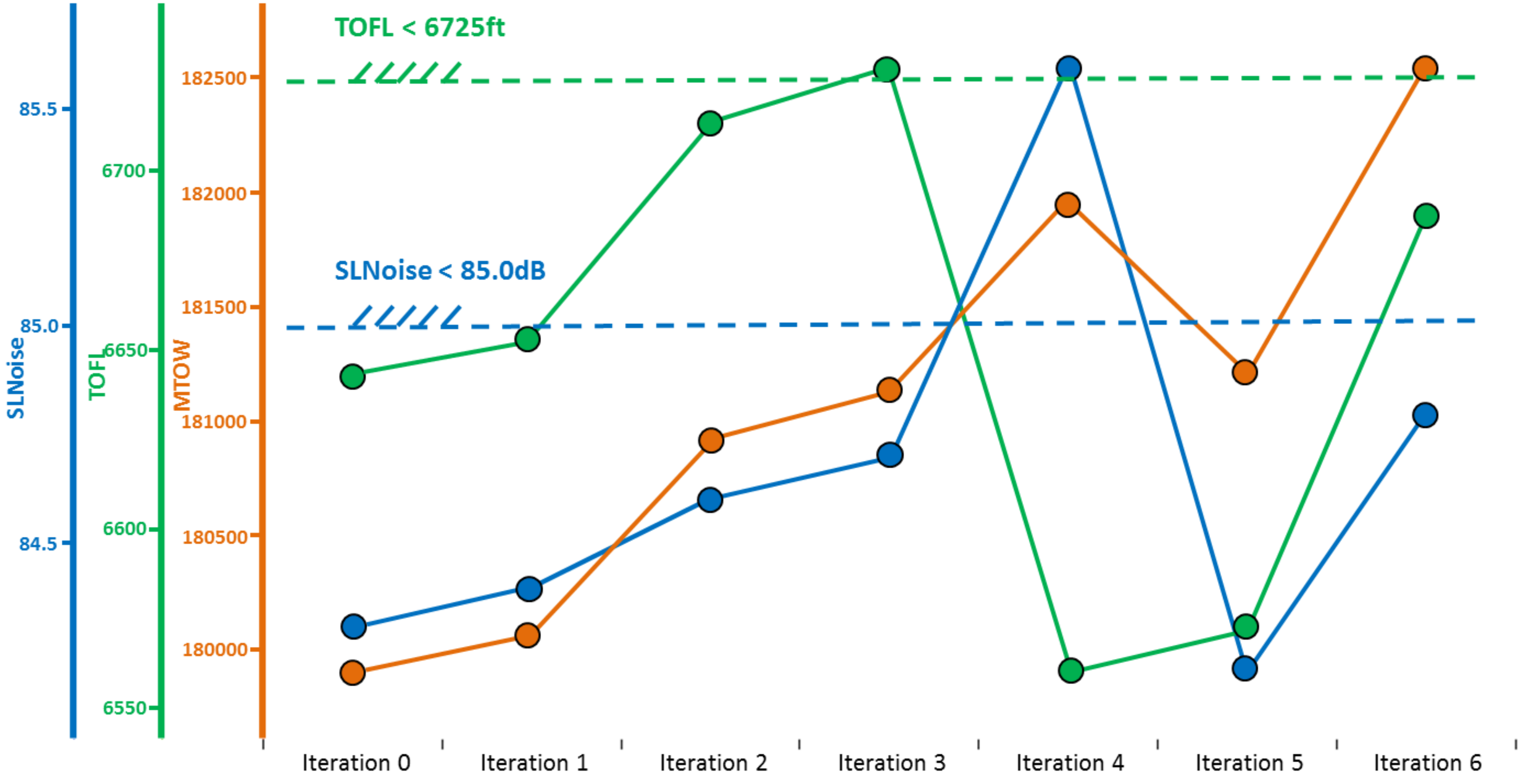


Figure 5.3: Variations in MTOW, TOFL, and SLNoise during Design Iterations

There are three significant causes for design change and rework. First, when the design team learns something very late in the design process that invalidates the prior assumption(s). This was experienced when it was discovered very late during the integration phase that the assembly of aileron EMA and heat pipe could not be fitted in the wing, which resulted in design rework or iteration. This type of design change or rework could also happen because of changes in the customer requirements. Second, when the design team makes critical decision(s) very early in the design phase, without having sufficient knowledge to make better decisions. This cause was also experienced when the design team took the decision of using all-electric systems architecture very early without sufficient knowledge. The third cause for design rework occurs when decisions of one team constrain the decisions of other team. This cause was experienced when the decision of the aerodynamics and flight control systems team to increase the TCR_W resulted in violation of take-off field length constraint, which affected the decision of propulsion team to use 29000.0lb SLST engines. Consequently, the propulsion team had to rework (increase the SLST) due to the decision made by other teams.

All the design rework or iteration required new design studies to be initiated, i.e. reformulating the optimisation problem by considering minimum change to the existing baseline aircraft. The design changes at the later stages are more expensive to rectify compared to synthesizing and analyzing sets of solutions early in the design process. The proposed methodology described in Chapter 4 considers the set of design solutions, instead of selecting one solution and then iteratively modifying it until all the requirements or constraints are met. Although it may appear that a lot of work needs to be performed at the start when using the proposed methodology, it saves time by reducing the number of design changes or iterations required later when using tradition PBD approach. In other words, the proposed methodology reduces the risks of design rework and increases the probability of success in finding best or optimal solution by considering a set of solutions and delaying critical decisions until more design knowledge is available.

## 5.3 Experts Feedback and Opinion

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 approach used in the industry, and the associated challenges such as required resources (people, time, cost, tools, etc.) and the possibility to introduce it in the organisation'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 of industrial experts 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 or 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 for designing passenger aircraft families provides great development advantages when used for designing innovative aircraft families, requiring many design iterations. The panel identified that the proposed methodology for designing passenger aircraft families still faces a challenge from a (computational and human) resources point of view during detailed design stages where it would be difficult to maintain and carry forward many design solutions together.

## 5.4 Summary and Conclusions

In this chapter, the evaluation of the proposed methodology was conducted by means of qualitative assessment. First, in order to compare the proposed methodology with the traditional approach, the same application case-study (described in chapter 4) was executed by using the traditional PBD approach. Next, the application case-study and the two approaches (proposed methodology and traditional approach) along with their results 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 semi-structured questionnaire and informal discussion was used to capture their feedback.

The results of the evaluation indicate that the traditional point-based design (PBD) approach is highly iterative and leads to convergence problems especially when designing complex innovative products. The proposed methodology is indeed expected to enable a more systematic exploration of wider design spaces by identifying several feasible or satisfactory solutions, hence providing more freedom of choice for designers. The proposed methodology allows parallel design and analysis of the major components and systems architectures for multiple aircraft family solutions. Although it may appear that a lot of work needs to be performed at the start when using the proposed methodology, it saves time by reducing the number of design changes or iterations required later when using tradition approach.

It is found that while the demonstrated enablers are reaching a stage of sufficient maturity, allowing a multitude of aircraft family solutions (including systems architectures) to be synthesised and analysed rapidly and simultaneously, this still is expected to present a challenge from organizational process and resources (people, computational) point of view.

# Chapter 6

# Summary and Conclusions

## 6.1 Introduction

This chapter concludes the main body of this thesis by presenting the key findings obtained from the research work. The summary of the research is presented in Section 6.2 where the aim and objectives (listed in Section 1.4) set for the current research are revisited. Next, the key findings of the current research work are summarised in Section 6.3. Following that, the main contributions to knowledge resulting from the research work are summarised in Section 6.4. Finally, the limitations of the proposed methodology and the recommendations for future work are listed in Section 6.5.

## 6.2 Summary of Research

The aim of the research was to develop a methodology for designing passenger aircraft families, which provides an environment for designers to interactively explore wider design spaces and foster innovation. The research was organised into three stages.

The first stage of the research work was concerned with the investigation of the current state-of-the-art in the field of passenger aircraft family design. In order to develop an effective methodology for designing passenger aircraft families, current trends for designing passenger aircraft families need to be investigated. Therefore, the first objective was set as follow:

> **Objective 1**: Investigate and identify the current trends used for designing passenger aircraft families in the industry.

In order to achieve the Objective 1, a classification (taxonomy) of aircraft family trends was proposed. The proposed classification of aircraft family trends is based on two top-level aircraft requirements (TLARs), i.e. minimum number of passengers and the minimum range. It was observed that there are three trends followed when designing passenger aircraft family variants (described in Figure 1.3). However, it was identified that there is currently one trend missing, i.e. increasing the number of passenger capacity while keeping the range similar.

The second stage of the research work involved the development of the methodology for designing passenger aircraft families. From the literature review, it was identified that the main problem with the existing methods is the iterative design process which employs optimisation-based, sequential (synthesis, analyse, and modify) approach. These 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 optimiser, may be infeasible due to the factors not considered by the models such as manufacturing, maintenance and novel technologies, leading to many nugatory design rework iterations. One of the prevailing convergent design processes (found in literature), which shows significant potential, is the set-based design (SBD) process (developed by Toyota automotive company). It provides the designers more freedom by delaying the critical decisions, as more knowledge is gained. In other words, it encourages the designers to foster innovation by preventing them from immediately elaborating on the first concept or architecture that comes into mind, which may not be the best. Although several research papers discuss the expected benefits of the SBD process, there is no formal methodology available in the literature that guides the designers how to implement the SBD process practically. The existing literature on SBD focuses on defining the principles only, without providing potential enablers or methods for implementing those principles. Enablers for rapidly synthesising and analysing the multitude of design solutions are the key to successfully implement the SBD process. It was discovered that there is a need to develop a formal set-based design methodology with potential associated enablers for designing passenger aircraft families. The second objective was, therefore, set as follow:

> **Objective 2**: Develop a formal methodology for designing passenger aircraft families at the early design stages, enabling designers to foster innovation, and interactively explore wider design spaces.

In order to achieve Objective 2, a novel methodology for designing passenger aircraft families is proposed that embraces the principles of the set-based design (SBD) paradigm 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. This approach has the advantage of reducing design rework, resulting from the wrong design decisions made earlier. Objective 2 has been achieved by integrating the set-theory principles and model-based design exploration methods. The proposed methodology for designing passenger aircraft families is divided into three phases: stakeholder needs mapping, synthesis and analysis, and narrowing-down.

Another limitation associated with the existing methods for designing passenger aircraft families is that these methods do not consider systems architectures at the early design stages. Instead, a top-down approach is used, where the aircraft configurations are frozen (by selecting a single systems architecture fairly early) before moving on to the systems architectures analysis and design. The systems architectures are, therefore, optimised 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. In order to provide designers an environment where they can foster innovation, the third objective was set as follow:

> **Objective 3**: Incorporate systems architectures analysis and design earlier into aircraft family conceptual design synthesis, in order to conduct systems technologies trade-off.

In order to achieve objective 3, fast physics-based computational models for systems architectures are incorporated within the conceptual design stage. In order to analyse the impact of systems architectures at the aircraft and mission level, three performance parameters of the systems architectures are considered, i.e. mass, cost, and bleed-air and shaft-power off-takes. By considering the set of systems architectures, the designers are able to conduct quick trade-off and mitigate risks associated with innovative technologies.

In addition to the development of passenger aircraft family design methodology, key enablers were identified and/or developed to support the development of aircraft family design methodology. Chapter 3 presents the proposed methodology along with different fit for purpose key enablers, whereas Chapter 4 demonstrates the methodology by using an application case-study.

The third stage of the research work was concerned with the evaluation of the proposed methodology, which was performed by means of qualitative assessment. First, in order to compare the proposed approach with the traditional approaches, the same application test-case (described in chapter 4) was executed by using the traditional optimisation-based approach. Next, the application case-study and the two approaches along with their results 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 semi-structured questionnaire and informal discussion was used to capture their feedback. Chapter 5 summarises the discussions and the feedback obtained from the industrial experts panel.

## 6.3 Research Findings

In this section, the key findings resulting from the present research work are summarised. The results of the evaluation indicate that:

1. The proposed methodology is expected to enable a more systematic exploration of wider design spaces by identifying several feasible or satisfactory solutions, hence providing more freedom of choice for designers. It allows parallel analysis and design of major components and systems for multiple aircraft family solutions, which shortens the overall design time. Although it may appear that a lot of work needs to be performed at the start when using the proposed methodology, it saves time by reducing the number of design changes or iterations required later when using tradition approach.

2. The proposed methodology provides 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 enables the integration of systems architectures analysis and design within the conceptual aircraft synthesis and design, allowing an instantaneous investigation of the impact of system architecture modifications on the aircraft and mission performance.

3. It is found that while the demonstrated enablers are reaching a stage of sufficient maturity, allowing a multitude of aircraft family solutions (including systems architectures) to be synthesised and analysed rapidly and simultaneously, this still is expected to present a challenge from organizational process and resources (people, computational) point of view.

## 6.4 Contributions to Knowledge

The contributions to knowledge resulting from the current research work are summarised below.

1. The main contribution to knowledge is the development of a novel set-based methodology for designing passenger aircraft families. This thesis presents the first attempt to formalise the passenger aircraft family design methodology by integrating set theory principles and model-based design exploration methods. The methodology differs significantly from the existing passenger aircraft family design methods: It considers a set of multiple aircraft family solutions from the outset by integrating major components sets and systems architectures set, which is then gradually narrowed. This allows the designers to systematically explore wider design spaces and gain knowledge while delaying critical decisions. In turn, this provides greater freedom at the later stages of the design process.

2. In order to develop the proposed methodology, a classification (taxonomy) of aircraft family trends is proposed. The proposed classification is based on two TLARs, i.e. the minimum number of passengers and the minimum range. It was identified that there is currently one trend missing, i.e. increasing the number of passenger capacity while keeping the range similar.

3. Unlike existing methods for designing passenger aircraft families, the proposed methodology incorporates early systems architectures analysis and

design. A method for modelling entire systems architectures (using fast physics-based computational models) within the conceptual design stage is used that enables the designers to conduct quick trade-off and mitigate risks associated with innovative technologies, resulting in reduced design rework or iterations. In order to analyse the impact of systems architectures at the aircraft and mission level, three performance parameters of the systems architectures are considered, i.e. mass, cost, and bleed-air and shaft-power off-takes. Furthermore, a fast parametric aircraft geometry tool is developed where system components are represented by cuboid, sphere, and cylinder in order to analyse the systems' components physical layout and their connections in the aircraft geometry, which allows to identify integration problems (clashes) between systems components in the early design stage.

4. A constraint analysis method using iso-contours is proposed for the down-selection of aircraft family set. The method divides the multi-dimensional design space into multiple 2D projections (slices) that can be used to gain insight into the topology of the feasible design space. The novelty comes from the fact that the proposed method does not require new evaluations of the computational models, instead the previously obtained results from the set generation are used by using interpolation in order to compute the constraints iso-contours. This makes the method well-suited for design space exploration at the early stage where designers can interactively move the constraints iso-contours in real-time. Furthermore, it offers flexibility to perform a sensitivity analysis of design variables towards different constraints to invoke what-if analysis in order to better understand the design space.

## 6.5 Future Work

There are a few limitations associated with the proposed methodology, which could be addressed in the future in order to improve the work presented in this thesis.

1. The proposed methodology is limited to the conceptual design stage. Carrying multiple aircraft family solution in the detailed design stage was not considered in this research. Although the approach can be applied in the

detailed design stage, it needs to be evaluated, i.e. how many aircraft family solutions can be carried forward simultaneously into the detailed design stage.

2. In this research, set of aircraft configurations were not considered. Future work may incorporate and evaluate different configurations (e.g. conventional tube-wing configuration, strut-brassed, joined wing, blended wing body) for aircraft family design.

3. The application case-study was limited to common wing, empennage, and systems architecture, whereas the fuselage was considered exclusive among family variants. The application test-case can be extended to include the case where fuselage may be common with exclusive wings among family variants, a concept sometimes called as modular wing. This will result in optimum wing for each airline for increased efficiency.

4. Down-selection and filtering of the aircraft family solutions was conducted by using performance constraints. Other factors, such as overall thermal management, maintenance, and -ilities (such as complexity, reliability, etc.) were not considered during the down-selection phase for the application case-study. Future research work may extend the application of the proposed methodology by developing metrics for evaluating aircraft family solutions.

5. One of the benefits of the proposed methodology for designing passenger aircraft families is that it enables the designers to explore wider design spaces and gain knowledge, which is the key for making better decisions. After a multitude of aircraft family solutions are synthesised and analysed, infeasible and inferior aircraft family solutions may be discarded. The associated knowledge for discarding a particular solution should be captured and stored in a database for later use. For instance, if an aircraft family solution is rejected due to a lower TRL of a particular technology, then this information for discarding should be stored in a database (rather than in designer's mind). The proposed methodology can be extended to incorporate the knowledge rationale capturing and storing mechanism.

6. For the current research, the computational (mathematical) models for systems architectures did not consider the modelling and sizing of constituent components. Instead, the parameters (e.g. required power off-take and mass)

for the whole systems were estimated. A direction for future work is to include the components modelling and (physical) sizing for the assessment of systems architectures set.

# Appendix A

# Computational Models

This appendix contains the Modelica computational models for selected aircraft systems used in the current research.

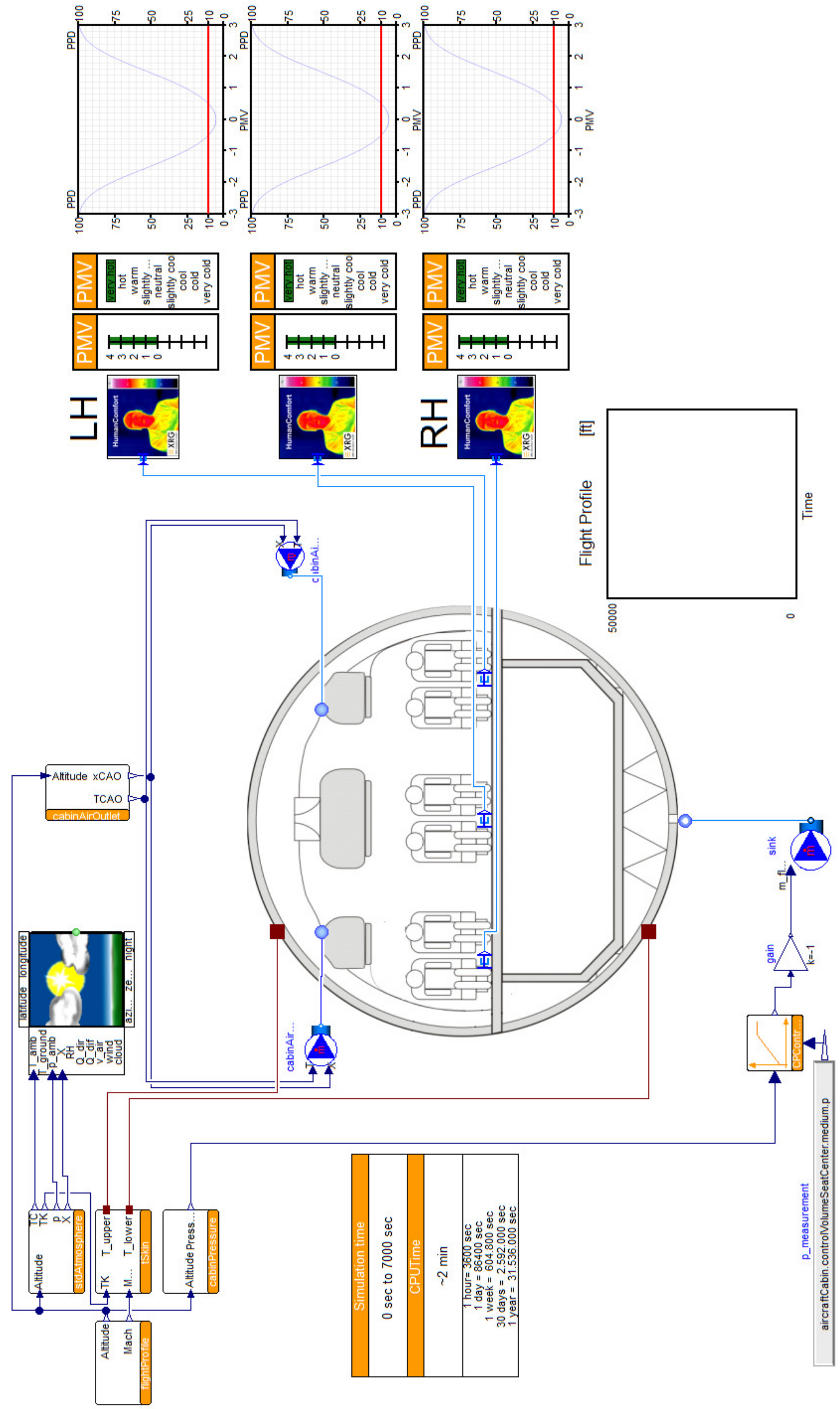


FIGURE A.1: Environmental Control System Model

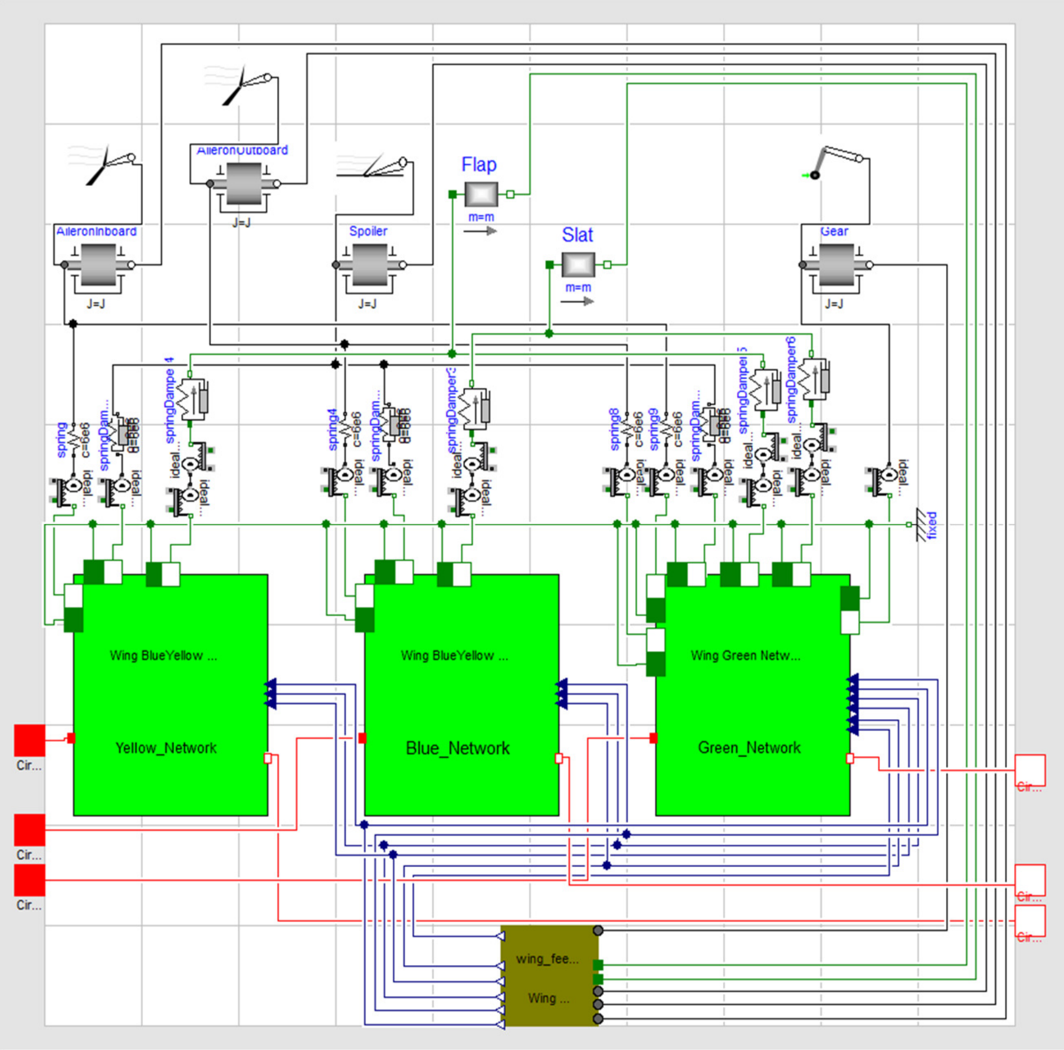


FIGURE A.2: Flight Control System Model

# References

[1] K. Willcox and S. Wakayama. Simultaneous optimization of a multiple-aircraft family. *Journal of Aircraft*, 40(4):616–622, 2003.

[2] Leonardo Versiani Cabral and Pedro Paglione. Conceptual design of families of aircraft using multi objective design optimization theory and genetic algorithm techniques. In *6th World Congresses of Structural and Multidisciplinary Optimization*, 30 May - 03 June 2005.

[3] Bryan D'Souza and Timothy W. Simpson. A genetic algorithm based method for product family design optimization. *Engineering Optimization*, 35(1):1–18, 2003.

[4] James Allison, Brian Roth, Michael Kokkolaras, Ilan Kroo, and Panos Y. Papalambros. Aircraft family design using decomposition-based methods. In *Proceedings of the 11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2006.

[5] Brian Douglas Roth. *Aircraft family design using enhanced collaborative optimization*. ProQuest, 2008.

[6] David G. Ullman. *The Mechanical Design Process*. McGraw-Hill, Boston, Mau., 3rd edition, 2003. ISBN 0072373385.

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

[8] Niall O'Keeffe. Caution welcomed: Boeing 737 max, 2011.

[9] Dieter Scholz. Aircraft systemsreliability, mass power and costs. In *European Workshop on Aircraft Design Education*, 2002.

[10] Ian Moir and Allan Seabridge. *Aircraft Systems: Mechanical, electrical and avionics subsystems integration*. John Wiley & Sons, West Sussex, England, 3rd edition, 2008.

[11] Daniel P. Raymer. *Aircraft Design: A Conceptual Approach.* AIAA (American Institute of Aeronautics & Astronautics), 5th edition, 2012.

[12] Denis Howe. *Aircraft Conceptual Design Synthesis.* Professional Engineering Publishing Limited, London, 2000.

[13] Michael A. Dornheim. Electric cabin. *Aviation Week & Space Technology*, 162(13):47–50, 03/28 2005.

[14] Timothy W. Simpson, Zahed Siddique, and Roger Jianxin Jiao. *Product platform and product family design: methods and applications.* Springer, 2006.

[15] John E. Funk, Joseph R. Harber, and Lisa Morin. Future military common aircraft development opportunities. In *44th AIAA Aerospace Sciences Meeting and Exhibit*, 9 - 12 January 2006.

[16] IIan Berlowitz. Passenger airplane conversion to freighter. In *29th Congress of the International Council of the Aeronautical Sciences*, 7-12 September 2014.

[17] Pavel Zhuravlev and Vladimir Zhuravlev. Significance of modifications for development of passenger airplanes. *Aircraft Engineering and Aerospace Technology*, 84(3):172–180, 2012.

[18] Fairuz Izzuddin Romli. *A strategic planning methodology for aircraft redesign.* ProQuest, 2009.

[19] Marco Nunez and Marin D. Guenov. Design-exploration framework for handling changes affecting conceptual design. *Journal of Aircraft*, 50(1):114–129, 2013.

[20] Durward K. Sobek, Allen C. Ward, and Jeffrey K. Liker. Toyota's principles of set-based concurrent engineering. *Sloan management review*, 40(2):67–84, 1999.

[21] David J. Singer, Norbert Doerry, and Michael E. Buckley. What is set-based design? *Naval Engineers Journal*, 121(4):31–43, 2009.

[22] Engineering Accreditation Commission. Accreditation board for engineering and technology. *Criteria for Accrediting Engineering Programs*, 2007.

[23] Nigel Cross. *Engineering design methods: strategies for product design.* John Wiley & Sons, 2008.

[24] Seyyed Khandani. Engineering design process. 2005.

[25] David Holston. *The Strategic Designer: Tools & Techniques for Managing the Design Process.* How Books, 2011.

[26] George E. Dieter. *Engineering design: a materials and processing approach.* McGraw-Hill, 2000.

[27] Michael J. French. *Conceptual design for engineers.* Springer, 1985.

[28] John Clarkson and Claudia Eckert. *Design process improvement: a review of current practice.* Springer Science & Business Media, 2010.

[29] Gerhard Pahl, Wolfgang Beitz, Jrg Feldhusen, and Karl-Heinrich Grote. *Engineering design: a systematic approach*, volume 157. Springer, 3rd edition, 2007.

[30] Stuart Pugh. *Total design: integrated methods for successful product engineering.* Addison-Wesley, 1991.

[31] NFM Roozenburg and NG Cross. Models of the design process: integrating across the disciplines. *Design Studies*, 12(4):215–220, 1991.

[32] Vladimir Hubka. *Principles of engineering design.* Elsevier, 2013.

[33] Norbert FM Roozenburg and Johannes Eekels. *Product design: fundamentals and methods*, volume 2. Wiley Chichester, 1995.

[34] NFO Evbuomwan, S. Sivaloganathan, and A. Jebb. A survey of design philosophies, models, methods and systems. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 210 (4):301–320, 1996.

[35] Clive L. Dym, Patrick Little, and Elizabeth Orwin. *Engineering Design: A Project-Based Introduction.* John Wiley & Sons, 4th edition, 2013.

[36] Thomas J. Howard, Stephen J. Culley, and Elies Dekoninck. Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies*, 29(2):160–180, 2008.

[37] Michael Lawson and HM Karandikar. A survey of concurrent engineering. *Concurrent Engineering*, 2(1):1–6, 1994.

[38] Biren Prasad. *Concurrent engineering fundamentals*, volume 1. Prentice Hall Englewood Cliffs, NJ, 1996.

[39] Steven C. Wheelwright and Kim B. Clark. *Revolutionizing product development: quantum leaps in speed, efficiency, and quality.* Simon and Schuster, 1992.

[40] Joshua Ian Bernstein. Design methods in the aerospace industry: looking for evidence of set-based practices, 1998.

[41] Allen Ward, Jeffrey K. Liker, John J. Cristiano, and Durward K. Sobek. The second toyota paradox: How delaying decisions can make better cars faster. *Sloan management review*, 1995.

[42] Y-E Nahm and H. Ishikawa. Novel space-based design methodology for preliminary engineering design. *The International Journal of Advanced Manufacturing Technology*, 28(11-12):1056–1070, 2006.

[43] Robert G. Cooper. Managing technology development projects. *Research-Technology Management*, 49(6):23–31, 2006.

[44] Eric Bonabeau, Neil Bodick, and Robert W. Armstrong. A more rational approach to new-product development. *Harvard business review*, 86(3):96, 2008.

[45] Brian M. Kennedy, Durward K. Sobek, and Michael N. Kennedy. Reducing rework by applying setbased practices early in the systems engineering process. *Systems Engineering*, 17(3):278–296, 2014.

[46] Yoon-Eui Nahm and Haruo Ishikawa. Representing and aggregating engineering quantities with preference structure for set-based concurrent engineering. *Concurrent Engineering*, 13(2):123–133, 2005.

[47] Masato Inoue, Yoon-Eui Nahm, and Haruo Ishikawa. Application of preference set-based design method to multilayer porous materials for sound absorbency and insulation. *International Journal of Computer Integrated Manufacturing*, 26(12):1151–1160, 2013.

[48] Walter L. Mebane, Craig M. Carlson, Chris Dowd, David J. Singer, and Michael E. Buckley. Set-based design and the ship to shore connector. *Naval Engineers Journal*, 123(3):79–92, 2011.

[49] Jeffrey K. Liker and James M. Morgan. The toyota way in services: the case of lean product development. *The Academy of Management Perspectives*, 20 (2):5–20, 2006.

[50] Michael N. Kennedy. Product development for the lean enterprise. *Richmond, VA: The*, 2003.

[51] Department of Defence. *Systems Engineering Fundamentals*. Department of Defence (DoD), United States, 2001.

[52] Vivek D. Bhise. *Designing Complex Products with Systems Engineering Processes and Techniques*. CRC Press, 2013.

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

[54] ISO/IEC 15288. Systems and software engineering - system life cycle processes, 2008.

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

[56] Stephen J. Kapurch. *NASA Systems Engineering Handbook*. DIANE Publishing, 2010.

[57] Kevin Forsberg and Harold Mooz. The relationship of systems engineering to the project cycle. *Engineering Management Journal*, 4(3):36–43, 1992.

[58] Charles Dickerson and Dimitri N. Mavris. *Architecture and principles of systems engineering*. CRC Press, 2009.

[59] Winston W. Royce. Managing the development of large software systems. In *proceedings of IEEE WESCON*, volume 26, pages 328–388. Los Angeles, 1970.

[60] Barry W. Boehm. A spiral model of software development and enhancement. *Computer*, 21(5):61–72, 1988.

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

[62] Mohammad H. Sadraey. *Aircraft Design: A Systems Engineering Approach.* John Wiley & Sons, West Sussex, UK, 2012.

[63] Ajoy Kumar Kundu. *Aircraft design.* Cambridge University Press, 2010.

[64] Nam P. Suh. Axiomatic design of mechanical systems. *Journal of Mechanical Design*, 117(B):2–10, 1995.

[65] Nam P. Suh. Axiomatic design theory for systems. *Research in engineering design*, 10(4):189–209, 1998.

[66] Nam P. Suh. *Axiomatic Design: Advances and Applications.* Oxford University Press, 2001.

[67] Jason D. Hintersteiner and Richard C. Zimmerman. Implementing axiomatic design in the systems engineering process: an axiomatic design capability maturity model. In *First International Conference on Axiomatic Design (ICAD2000), Institute for Axiomatic Design, Cambridge, MA*, pages 9–17, 2000.

[68] Semyon D. Savransky. *Engineering of creativity: Introduction to TRIZ methodology of inventive problem solving.* CRC Press, 2000.

[69] Su Mi Dahlgaard-Park and K. Narasimhan. Inventive thinking through triz: A practical guide. *The TQM Magazine*, 18(3):312–314, 2006.

[70] Kai Yang and Hongwei Zhang. A comparison of triz and axiomatic design. In *INTERNATIONAL CONFERENCE ON AXIOMATIC DESIGN*, volume 1, pages 235–242, 2000.

[71] Madara Ogot. Conceptual design using axiomatic design in a triz framework. *Procedia Engineering*, 9:736–744, 2011.

[72] John R. Hauser and Don Clausing. The house of quality. *Harvard Business Review*, 66(May-June):63–73, 1988.

[73] J. Martins and A. B. Lambe. Multidisciplinary design optimization: Survey of architectures. *AIAA Journal*, 2012.

[74] AJ de Wit and F. van Keulen. Overview of multi-level and/or multi-disciplinary optimization strategies for preliminary aircraft design optimization. 2010.

[75] Panos Y. Papalambros and Douglass J. Wilde. *Principles of optimal design: modeling and computation.* Cambridge university press, 2000.

[76] Timothy W. Simpson. *A concept exploration method for product family design.* PhD thesis, Georgia Institute of Technology, 1998.

[77] Timothy W. Simpson, Jonathan RA Maier, and Farrokh Mistree. A product platform concept exploration method for product family design. In *ASME Design Theory and Methodology*, volume 9, pages 1–219, 1999.

[78] Timothy W. Simpson, Jonathan R. Maier, and Farrokh Mistree. Product platform design: method and application. *Research in engineering Design*, 13(1):2–22, 2001.

[79] Marc H. Meyer and Alvin P. Lehnerd. *The power of product platforms.* Simon and Schuster, 1997.

[80] F. Mistree, O. F. Hughes, and B. A. Bras. The compromise decision support problem and the adaptive linear programming algorithm. *Structural Optimization: Status and Promise, Kamat, MP, ed., AIAA, Washington, DC*, pages 247–286, 1993.

[81] James P. Ignizio. Multiobjective mathematical programming via the multiplex model and algorithm. *European Journal of Operational Research*, 22 (3):338–346, 1985.

[82] Timothy W. Simpson. Product platform design and customization: Status and promise. *AI EDAM: Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 18(01):3–20, 2004.

[83] Raviraj U. Nayak, Wei Chen, and Timothy W. Simpson. A variation-based method for product family design. *Engineering Optimization*, 34(1):65–81, 2002.

[84] Sigurd A. Nelson, Matthew B. Parkinson, and Panos Y. Papalambros. Multicriteria optimization in product platform design. *Journal of Mechanical Design*, 123(2):199–204, 2001.

[85] George Q. Huang, Li Li, and Lothar Schulze. Genetic algorithm-based optimisation method for product family design with multi-level commonality. *Journal of Engineering Design*, 19(5):401–416, 2008.

[86] Achille Messac, Michael P. Martinez, and Timothy W. Simpson. Effective product family design using physical programming. *Engineering Optimization*, 34(3):245–261, 2002.

[87] Timothy W. Simpson and Brayan S. Dsouza. Assessing variable levels of platform commonality within a product family using a multiobjective genetic algorithm. *Concurrent Engineering*, 12(2):119–129, 2004.

[88] Gabriel Hernandez, Janet K. Allen, and Farrokh Mistree. Platform design for customizable products as a problem of access in a geometric space. *Engineering Optimization*, 35(3):229–254, 2003.

[89] Ryan Fellini. *A model-based methodology for product family design.* PhD thesis, University of Michigan, 2003.

[90] Henri J. Thevenot, Jyotirmaya Nanda, and Timothy W. Simpson. A methodology to support product family redesign using genetic algorithm and commonality indices. In *ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 1009–1018. American Society of Mechanical Engineers, 2005.

[91] Aida Khajavirad, Jeremy J. Michalek, and Timothy W. Simpson. A decomposed genetic algorithm for solving the joint product family optimization problem. In *3rd AIAA multidisciplinary design optimization specialists conference. Honolulu, HI*, 2007.

[92] Ian Sobieski and Ilan Kroo. Aircraft design using collaborative optimization. In *Proceedings of the 34th AIAA Aerospace Sciences Meeting*, 1996.

[93] Ian Patrick Sobieski. *Multidisciplinary design using collaborative optimization.* PhD thesis, Stanford University, 1998.

[94] Robert Braun, Peter Gage, Ilan Kroo, and lan Sobieski. Implementation and performance issues in collaborative optimization. 1996.

[95] RD Braun, IM Kroo, and AA Moore. Use of the collaborative optimization architecture for launch vehicle design. In *Proceedings of the 6th AIAA/-NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, 1996.

[96] Robert David Braun. *Collaborative optimization: an architecture for large-scale distributed design.* PhD thesis, Stanford University, 1996.

[97] Valerie Michelle Manning. *Large-scale design of supersonic aircraft via collaborative optimization*. PhD thesis, Stanford University, 1999.

[98] Natalia M. Alexandrov and Robert Michael Lewis. Analytical and computational aspects of collaborative optimization for multidisciplinary design. *AIAA Journal*, 40(2):301–309, 2002.

[99] Nestor Michelena, Hyung Min Kim, and PY Papalambros. A system partitioning and optimization approach to target cascading. In *Proceedings of the 12th International Conference on Engineering Design*, volume 2, pages 1109–1112, 1999.

[100] Hyung Min Kim, Nestor F. Michelena, Panos Y. Papalambros, and Tao Jiang. Target cascading in optimal system design. *Journal of mechanical design*, 125(3):474–480, 2003.

[101] James Allison, David Walsh, Michael Kokkolaras, Panos Y. Papalambros, and Matthew Cartmell. Analytical target cascading in aircraft design. In *44th AIAA aerospace sciences meeting and exhibit*, pages 9–12, 2006.

[102] R. Choudhary, A. Malkawi, and PY Papalambros. Analytic target cascading in simulation-based building design. *Automation in Construction*, 14(4):551–568, 2005.

[103] Hyung Min Kim, Michael Kokkolaras, Loucas S. Louca, George J. Delagrammatikas, Nestor F. Michelena, Zoran S. Filipi, Panos Y. Papalambros, Jeffrey L. Stein, and Dennis N. Assanis. Target cascading in vehicle redesign: a class vi truck study. *International Journal of Vehicle Design*, 29 (3):199–225, 2002.

[104] Michael Kokkolaras, L. Louca, G. Delagrammatikas, N. Michelena, Z. Filipi, P. Papalambros, J. Stein, and D. Assanis. Simulation-based optimal design of heavy trucks by model-based decomposition: An extensive analytical target cascading case study. *International Journal of Heavy Vehicle Systems*, 11 (3-4):403–433, 2004.

[105] Jeremy J. Michalek, Fred M. Feinberg, and Panos Y. Papalambros. Linking marketing and engineering product design decisions via analytical target cascading*. *Journal of Product Innovation Management*, 22(1):42–62, 2005.

[106] M. Kokkolaras, R. Fellini, H. M. Kim, N. F. Michelena, and P. Y. Papalambros. Extension of the target cascading formulation to the design of product families. *Structural and Multidisciplinary Optimization*, 24(4):293–301, 10/01 2002. URL http://dx.doi.org/10.1007/s00158-002-0240-0. J2: Struct Multidisc Optim.

[107] Nestor Michelena, Hyungju Park, and Panos Y. Papalambros. Convergence properties of analytical target cascading. *AIAA Journal*, 41(5):897–905, 2003.

[108] S. Tosserams. Analytical target cascading: convergence improvement by sub-problem post-optimality sensitivities, 2004.

[109] Harrison M. Kim, Wei Chen, and Margaret M. Wiecek. Lagrangian coordination for enhancing the convergence of analytical target cascading. *AIAA Journal*, 44(10):2197–2207, 2006.

[110] James Allison, Michael Kokkolaras, Marc Zawislak, and Panos Y. Papalambros. On the use of analytical target cascading and collaborative optimization for complex system design. In *6th world congress on structural and multidisciplinary optimization, Rio de Janeiro, Brazil*, pages 1–10. Citeseer, 2005.

[111] Robert H. Liebeck. Design of the blended wing body subsonic transport. *Journal of Aircraft*, 41(1):10–25, 2004.

[112] Abbie Griffin and John R. Hauser. The voice of the customer. *Marketing science*, 12(1):1–27, 1993.

[113] John R. Hauser. How puritan-bennett used the house of quality. *Sloan management review*, 34(3):61–70, 1993.

[114] Marco Nunez, Varun Chander Datta, Arturo Molina-Cristobal, Marin Guenov, and Atif Riaz. Enabling exploration in the conceptual design and optimisation of complex systems. *Journal of Engineering Design*, 23(10-11): 852–875, 2012.

[115] Jiju Antony. *Design of experiments for engineers and scientists*. Elsevier, 2014.

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

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

[118] Johan lvander, Bjrn Lundn, and Hampus Gavel. A computerized optimization framework for the morphological matrix applied to aircraft conceptual design. *Computer-Aided Design*, 41(3):187–196, 2009.

[119] Mogens Myrup Andreasen. *Machine design methods based on a systematic approachcontribution to a design theory.* PhD thesis, Lund University, Sweden, 1980.

[120] Claus Thorp Hansen. An approach to simultaneous synthesis and optimization of composite mechanical systems. *Journal of Engeering Design*, 6(3): 249–266, 1995.

[121] Harold Chestnut. *SYSTEMS ENGINEERING METHODS.* Wiley, 1967.

[122] Libish Kalathil Balachandran. *Computational workflow management for conceptual design of complex systems: an air-vehicle design perspective.* PhD thesis, Cranfield University, UK, 2007.

[123] LK Balachandran and MD Guenov. Computational workflow management for conceptual design of complex systems. *Journal of Aircraft*, 47(2):699–703, 2010.

[124] Marco Nunez, Varun Chander Datta, Arturo Molina-Cristobal, Marin Guenov, and Atif Riaz. Enabling exploration in the conceptual design and optimisation of complex systems. *Journal of Engineering Design*, 23(10-11): 852–875, 2012.

[125] Marin D. Guenov, Marco Nunez, Arturo Molina-Cristbal, Varun C. Datta, and Atif Riaz. Aircadiaan interactive tool for the composition and exploration of aircraft computational studies at early design stage. In *ICAS*, 7 - 12 September 2014.

[126] Richard Courant and Herbert Robbins. *What is Mathematics?: an elementary approach to ideas and methods.* Oxford University Press, 1996.

[127] Brenda M. Kulfan and John E. Bussoletti. Fundamental parametric geometry representations for aircraft component shapes. In *11th AIAA/ISSMO multidisciplinary analysis and optimization conference*, volume 6948. sn, 2006.

[128] MD Guenov, M. Nunez, A. Molina-Cristbal, V. Sripawadkul, V. Datta, and A. Riaz. Composition, management and exploration of computational studies at early design stage, to appear in: Vasile, m. and becerra, v. *Computational Intelligence in Aerospace Sciences*, 244, 2014.

[129] Salvatore Greco, Matthias Ehrgott, and Jos Rui Figueira. *Trends in multiple criteria decision analysis*, volume 142. Springer Science & Business Media, 2010.

[130] Pratyush Sen and Jian-Bo Yang. *Multiple criteria decision support in engineering design*. Springer Science & Business Media, 2012.

[131] C. L. Hwang and K. Yoon. *Multiple Attribute Decision Making: Methods and Applications*. Springer-Verlag, New York, 1981.

[132] Kalyanmoy Deb and Amrit Pratap. A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: Nsga-ii. 2002.

[133] Graham Warwick. Choose the future. *Aviation Week and Space Technology*, 173(26):44–44, 07/18 2011.

[134] J. A. Rosero, J. A. Ortega, E. Aldabas, and L. Romeral. Moving towards a more electric aircraft. *Aerospace and Electronic Systems Magazine, IEEE*, 22(3):3–9, 2007.

[135] Elwood H. Hunt, Don H. Reid, David R. Space, and Fred E. Tilton. Commercial airliner environmental control system: Engineering aspects of cabin air quality. In *Aerospace Medical Association annual meeting*, 1995.

[136] Jonathan H. Gould and Robert G. McGurgan. Flying test bed performance testing of high-bypass-ratio turbofans. *SAE International Journal of Aerospace*, 2(1):67–74, March 01 2010.

[137] Mike Sinnett. 787 no-bleed systems: Saving fuel and enhancing operational efficiencies, 2007.

[138] Dominique Van Den Bossche. The a380 flight control electrohydrostatic actuators, achievements and lessons learnt. In *25th Congress of the International Council of the Aeronautical Sciences*, September 2006.

[139] Alain Coutrot. Key technology enablers for the future of aeronautical equipment industry. In *25th Congress of the International Council of the Aeronautical Sciences*, September 2006.

[140] LA McCullers. Flops-flight optimization system. *Proceedings of Recent Experiences in Multidisciplinary Analysis and Optimization, Hampton, Virginia*, 1984.

[141] LA McCullers. Aircraft configuration optimization including optimized flight profiles. In *Proceedings of a Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization*, pages 395–412. NASA CP-2327, 1984.

[142] Imon Chakraborty, David Trawick, Dimitri N Mavris, Mathias Emeneth, and Alexander Schneegans. A requirements-driven methodology for integrating subsystem architecture sizing and analysis into the conceptual aircraft design phase. In *14th AIAA Aviation Technology, Integration, and Operations Conference*, 16 - 20 June 2014.

[143] Tim Lammering. *Integration of aircraft systems into conceptual design synthesis.* PhD thesis, Lehrstuhl und Institut für Luft-und Raumfahrtsysteme (ILR), 2014.

[144] Cyril de Tenorio. *Methods for collaborative conceptual design of aircraft power architectures.* Georgia Institute of Technology, 2010.

[145] Kazuki Shibata, Tomo Maedomari, Kenichi Rinoie, Noriko Morioka, and Hitoshi Oyori. Aircraft secondary power system integration into conceptual design and its application to more electric system. Technical report, SAE Technical Paper, 2014.

[146] Imon Chakraborty, Dimitri N Mavris, Mathias Emeneth, and Alexander Schneegans. A methodology for vehicle and mission level comparison of more electric aircraft subsystem solution: Application to the flight control actuation system. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2014.

[147] Oliver Meier and Dieter Scholz. A handbook method for the estimation of power requirements for electrical de-icing systems. In *Deutscher Luft-und Raumfahrt Kongress*, 2010.

[148] D Scholz. Development of a cae-tool for the design of flight control and hydraulic systems. In *SAE AeroTech Congress, Birmingham, UK*, 1995.

[149] KM Al-Kahlil, D Miller, and W Wright. Validation of thermal ice protection computer codes: Part 3–the validation. AIAA, 1997.

[150] Xiuxian Xia and Craig P Lawson. The development of a design methodology for dynamic power distribution management on a civil transport all electric aircraft. *Aerospace Science and Technology*, 25(1):125–131, 2013.