A STRATEGIC PLANNING METHODOLOGY

FOR AIRCRAFT REDESIGN

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A STRATEGIC PLANNING METHODOLOGY

FOR AIRCRAFT REDESIGN

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Dedicated to my late father and my loving mother

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LIST OF ABBREVIATIONS

AEA	All Electric Aircraft
AC	Alternating Current
AM	Actuator Module
CAD	Computer Aided Design
CE	Concurrent Engineering
CFAR	Change Favorable Representation
CM-EC	Collaborative Management of Engineering Changes
CPA	Change Propagation Analysis
CPM	Change Prediction Method
CSD	Constant Speed Drive
DBPRA	“Design for Assembly”-based Product Redesign Approach
DC	Direct Current
DFA	Design for Assembly
DML	Design Maturity Level
DoD	Department of Defense
DoE	Design of Experiments
DSM	Design Structure Matrix
DSTO	Defense Science and Technology Organization
EIA	Electronic Industries Alliance
ECM	Engineering Change Management
ECO	Engineering Change Order
ECP	Engineering Change Proposal

ECR	Engineering Change Request
ECU	Electronic Control Unit
EHA	Electrohydrostatic Actuation
EMA	Electromechanical Actuation
ERP	Enterprise Resource Planning
FBW	Fly by Wire
FLIR	Forward Looking Infrared Radar
FMEA	Failure Mode Effect Analysis
IEC	International Electrotechnical Commission
IFE	In-Flight Entertainment
IML	Interface Maturity Level
INCOSE	International Council on Systems Engineering
IPC	Intelligent Power Controller
IPPD	Integrated Product/Process Development
ISO	International Organization for Standardization
MAAP	Methodology for Assessing the Adaptability of Products
MEA	More Electric Aircraft
MIDAS	Memory for Initial Design of Aircraft Subsystems
MRL	Manufacturing Readiness Level
NASA	National Aeronautics and Space Administration
PBW	Power by Wire
PCU	Power Conversion Unit
PDM	Product Data Management
PEP	Productivity Enhancement Program
PFCC	Primary Flight Control Computer

PLM	Product Lifecycle Management
RSM	Response Surface Method
RSE	Response Surface Equation
SAF	System Adaptability Factor
SBF	Structure-Behavior-Function
SOP	Subtract-and-Operate
SPEC	Strategic Planning of Engineering Changes
SRL	System Readiness Level
SWOT	Strength, Weakness, Opportunity and Threat
TIES	Technology Identification, Evaluation and Selection
TML	Technology Maturity Level
TRL	Technology Readiness Level
VA	Value Analysis
VSCF	Variable Speed Constant Frequency

SUMMARY

Due to a progressive market shift to a customer-driven environment, the influence of engineering changes on the product's market success is becoming more prominent. This situation affects many long lead-time product industries including aircraft manufacturing. Derivative development has been the key strategy for many aircraft manufacturers to survive the competitive market and this trend is expected to continue in the future. Within this environment of design adaptation and variation, the main market advantages are often gained by the fastest aircraft manufacturers to develop and produce their range of market offerings without any costly mistakes. This realization creates an emphasis on the efficiency of the redesign process, particularly on the handling of engineering changes. However, most activities involved in the redesign process are supported either inefficiently or not at all by the current design methods and tools, primarily because they have been mostly developed to improve original product development. In view of this, the main goal of this research is to propose an aircraft redesign methodology that will act as a decision-making aid for aircraft designers in the change implementation planning of derivative developments.

The proposed method, known as Strategic Planning of Engineering Changes (SPEC), combines the key elements of the product redesign planning and change management processes. Its application is aimed at reducing the redesign risks of derivative aircraft development, improving the detection of possible change effects propagation, increasing the efficiency of the change implementation planning and also reducing the costs and the time delays due to the redesign process. To address these challenges, four research areas have been identified: baseline assessment, change propagation prediction, change impact analysis and change implementation planning. Based on the established requirements for the redesign planning process, several methods and tools that are identified within these research areas have been abstracted and adapted into the proposed SPEC method to meet the research goals.

The proposed SPEC method is shown to be promising in improving the overall efficiency of the derivative aircraft planning process through two notional aircraft system redesign case studies that are presented in this study.

CHAPTER I

RESEARCH MOTIVATION

"*Design is an evolutionary process and change is inevitable*."

- Phillips, C. (1987)

1.1 The Changing Marketplace

Manufacturers used to have absolute control over their product development, its price and its market direction [84]. Their operation during those early days of market economy was mainly based on mass production that focused on developing standardized mass products [323]. Similarly, commercial aircraft development was driven by technical and functional superiority at the expense of cost and time-to-market, which was inherited from military aircraft manufacturing [212]. This is synonym with the mantra "Higher, Faster, Farther" in aerospace products and systems development for many years [239]. Over the past few decades, this seller-dominated environment progressively evolves into a customer-driven market. This transition alters the competitive landscape between product manufacturers as they are forced to be more pro-active in responding to dynamic market demands [176].

In commercial aircraft industry today, several factors apart from performance capabilities are considered by airlines during their aircraft purchases. Among others, these include air traffic demands, fleet commonalities and price [88]. Accordingly, aircraft manufacturers need to reevaluate their past performance-based development and capture these elements into their offerings. Many aerospace companies today are striving to develop cheaper but higher performance products that are better tailored to their customer needs [77].

1.1.1 Dynamic Market Factors

Primary market factors: customers, competitors and technologies; and their effects on the dynamics of general product marketplace today are illustrated in Figure 1.

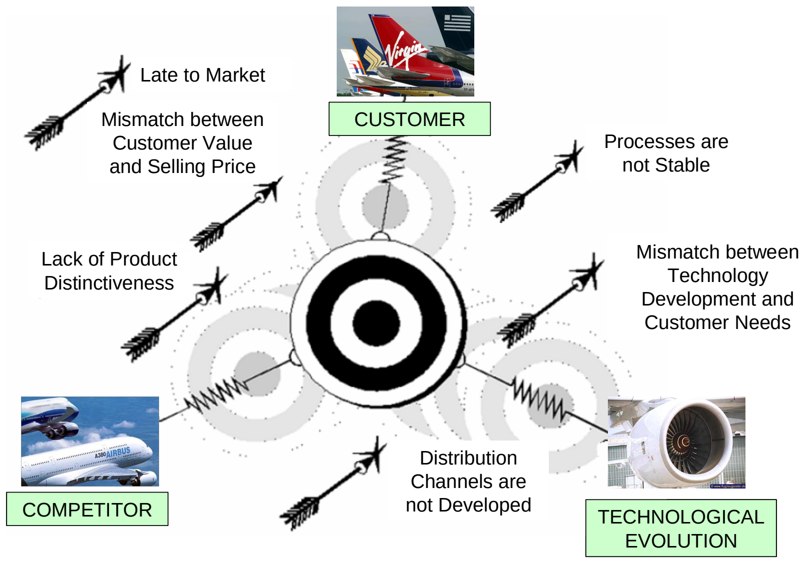

Figure 1: Dynamic Factors in Product Market [137]

Customers today are able to demand more innovative and customized products at a lower price since they are usually provided with multiple choices [137]. Subsequently, product demands become more diversified [226] and the market is increasingly fragmented by the rising trend of individualized mass products [175]. Product manufacturers have to revise their business strategy in response to increased market competition, which is intensified by rapid shortening of product lifecycle and emergence of new competitors due to market globalization [315]. This situation accelerates new technologies development that causes many existing components or subsystems to have a shorter technology half-life than their planned operational life [264]. The pursuit of new technologies could be necessary when matching technological innovation offered by other competitors or satisfying new market preferences or requirements beyond current product capabilities [117, 222]. Nonetheless, this can also set off a rapidly changing technology base for product development process [169] and challenges manufacturers to capture the novelties and uncertainties of fresh, immature technologies into their products within a shorter timeframe. It is imperative for them to evaluate potential risks and benefits of new technologies in their product prior to making any commitment [222].

A typical aircraft development can take up to about five years, depending on whether it is an original or a derivative design [266]. This long lead time allows high possibilities for changing market requirements and strategies while the aircraft is still under development. Air transportation demands, for example, is exceptionally sensitive to any irregularities in economic condition, demographic trend and fuel price fluctuation that are uncontrollable by aircraft manufacturers [26]. Furthermore, market globalization has raised the level of competition in this industry, mainly the rivalry between Airbus and Boeing companies in large commercial transport aircraft market segment [21, 174]. In July 2008, Bombardier became the latest competitor to enter that market with their C-series aircraft line [149]. If based on past trend, the increased competition will force these manufacturers to introduce fresh offerings at adequate market pace and become more flexible in their development. Moreover, aircraft operation in the air transportation system-of-systems is governed by a stringent aviation regulation that has been made stricter over the years, especially those regarding environmental issues. For instance, major actors in European aviation markets have set new requirements for aircraft by year 2020 to have 50% less CO_2 emission, 80% less NO_X emission and 50% less perceptible noise in comparison to current standard [16]. Although the rules are not frequently revised, it is a major advantage for manufacturers if their aircraft can perform well due to their operational longevity that is typically about 30 years [266]. On the whole, regulation changes and economics of air transportation market can be taken as the main drivers in the pursuit of new aircraft technologies.

Current dynamic market settings introduce new challenges to existing product design and development methods [40, 320] including those applied in aircraft manufacturing. Coping with these challenges in the best competitive manner is the main focus for current aircraft manufacturers, which drives the evolution of methods in their design and manufacturing processes [63].

1.1.2 Primary Market Challenges

Product industry in general is expected to be constantly pushed for a faster production of new, better quality products at lower costs by economic pressures [212, 326]. This entails development costs reduction, quality improvement and shorter process timeline for better time-to-market flexibility [84]. Product offerings also have to be relevant across different market fragments and produced at adequate market pace [173, 174]. On the whole, this can be summarized into two main market challenges.

Market Challenge 1: It is no longer sufficient to have better products than the competition but they also need to be rapidly brought into the market in a cost-effective manner [12, 244].

Planning of product lifecycle must consider the changing speed of its market environment and the development pace of its key competitors. In current market environment, product lead-time is as important as price, quality and innovation to ensure market success [307] and to gain advantages over its competition [57, 283]. Sharma et al. stated that "*getting better products faster to market is becoming very critical*" [292]. Time-to-market is vital in aircraft industry for manufacturers to acquire bigger market shares and to capitalize on newly available design features [50]. As in the case of Airbus A350 development, being second to Boeing B787 affects its market prospect among other things. By summer 2006, despite the promise of new technologies from Airbus A380 program, Airbus A350 failed to beat Boeing B787 in terms of sales order [90]. But in a recent market twist, production problems for Boeing B787 aircraft have delayed its market introduction and reduces lead-time advantages it has over Airbus A350, whose orders have since began to pile in [28, 223]. This example demonstrates the advantages of being first-in-the-market but also how fast market fortune could change if the development process is rushed and not properly managed.

Market Challenge 2: With a wide variation of market demands, a single design can no longer be expected to cover a broad range of the increasingly fragmented markets [84].

With this realization, traditional mass tailoring of product designs to a generalized set of customer needs is becoming a fading scenario [320]. Instead, product manufacturers need to be more innovative and flexible in producing varieties of their market offerings within a shorter timeframe [290]. In commercial aircraft manufacturing industry, this condition relates to derivative planning. Due to risky and costly investments to develop an original aircraft, it is arguably a big misstep for manufacturers not to capitalize on their successful designs whenever possible to extend their payoffs. Amid the pressures to introduce fresh designs for new market niches, competition between aircraft manufacturers heavily relies on derivative strategy. As new emerging market segments are forecasted, manufacturers will freshen up their aircraft offerings accordingly. In their latest aircraft development, Airbus and Boeing companies commit their efforts on totally different market directions. Airbus, with their jumbo A380 aircraft, foresees that the emerging market segments with greatest potential are those associated with ‘hub and spoke’ operations. In the meantime, Boeing puts their money on more direct flights between smaller airports with their B787 aircraft [27]. Since both original aircraft developments have been costly and risky, a good derivative plan is crucial to maximize market coverage of their future varieties and to pay off invested resources and efforts.

Faced with the abovementioned market challenges, it becomes rather necessary for many manufacturers to shift their paradigm from mass production to mass customization.

1.1.3 The Shift to Mass Customization and Product Redesign

Traditional mass production has been focused on manufacturing standardized products in large quantities at low unit cost [67]. However, as demands become more diversified, it is hard to have good market coverage with only a single product design [341]. In contrast, mass customization strategy aims to satisfy diverse customer needs by increasing product varieties while maintaining high efficiency of mass production [323, 342]. It principally transforms product development process into production of customer variants that rapidly adapts to varying market demands [117, 256]. Comparison between principles of mass production and mass customization is shown in Table 1 [341].

Table 1: Key Differences between Mass Production and Mass Customization

	Mass Production	**Mass Customization**
Focus	Efficient through stability and control	Variety and customization through flexibility and quick responsiveness
Goal	Developing, producing, marketing and delivering goods and services at prices low enough that nearly everyone can afford them	Developing, producing, marketing and delivering affordable goods and services with enough variety and customization so that nearly everyone finds exactly what they want
Key Features	Stable demand	Fragmented demand
	Large, homogenous markets	Heterogeneous niches
	Low cost, consistent quality, standardized goods and services	Low cost, high quality, customized goods and services
	Long product development cycles	Short product development cycles
	Long product life cycles	Short product life cycles

Paradigm shift to mass customization calls for changes in product development approach. Inness proposed that mass customization be achieved by designing original products with several variants, handling required product changes more efficiently and having flexible manufacturing capabilities [172]. In general manufacturing industry, all products can be grouped as either original or redesigned. An original product is defined as a novel design solution that is generated from scratch while a redesigned product involves adaptation of already known solutions [35]. Although most redesigned products are normally perceived as novel by customers, they do not involve extensive redevelopment of their predecessor [175]. This makes them more economically attractive to be developed than revolutionary designs under dynamic market environment such as today's [107]. Redesign approaches satisfy diverse market demands by upgrading or downgrading, enlarging or reducing and rearranging or modernizing parts of existing product designs [340]. By reusing already proven design elements and solution principles, it enables a faster development process and helps to leverage costs and risks for customized product varieties [238, 280]. Since many markets are rather ambivalent to accept new radical design [142], the resemblance of derivative products to past successful designs aids their marketability [120]. Based on these advantages, it can be concluded that product redesign strategies help to make mass customization, hence coping with dynamic marketplace, more economically feasible for product manufacturers [146].

The benefits of redesign strategies are often more pronounced in long lead-time, complex product industries [263]. Since original developments in these industries is commonly of high cost and risk, manufacturers frequently rely on incremental product improvements to satisfy new requirements [142]. This is apparent in commercial aircraft industry where design evolution of transport aircraft systems has always been made through revisions of their successful predecessors [118]. This development trend is expected to continue in the future unless there are new technological achievements for aircraft design process and/or some dramatic changes in governing aviation regulation [86]. Because redesign strategy is common in aircraft manufacturing, the utmost advantage is often gained by the fastest manufacturers to develop their range of aircraft options without any costly mistakes. This relates to current "Better, Faster, Cheaper" goal in aerospace industry [239], which puts a high emphasis on the efficiency of redesign planning. As depicted in Figure 2, Airbus has maximized its market shares by strategically producing their aircraft derivatives. Further discussion on current aircraft redesign strategies is presented in next chapter.

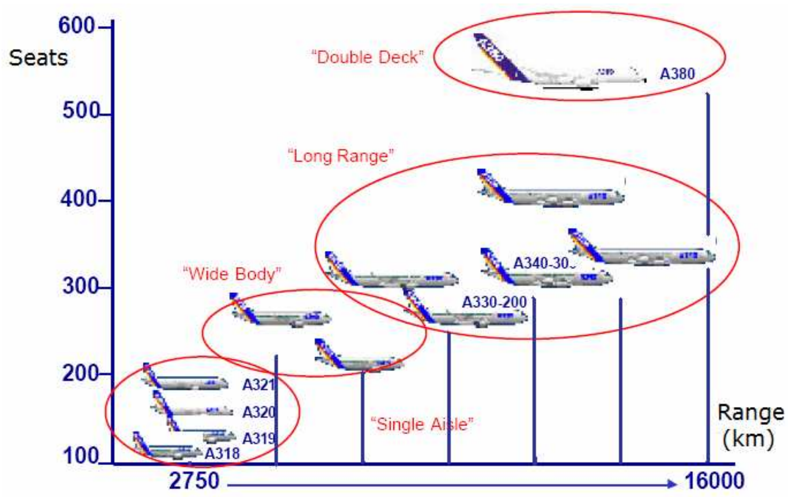

Figure 2: Families of Aircraft from Airbus [266]

Thus far, paradigm shift to mass customization in product manufacturing has been shown to focus on making design modifications [67]. In conjunction with this, product redesign has become an inevitable task in response to new market requirements [163]. At present, product development process is perceived as an art of making a series of changes on an existing product until it satisfies its driving requirements [82, 120]. Design changes have become more prominent throughout a product's entire lifecycle: from its conception until end of its operational life [82, 242, 273]. It is impossible to avoid having reiterations in product development process today [92, 242] and a key issue within this environment of design adaptation and variation is the handling of required design changes [175]. Due to high competitiveness of aircraft manufacturing business, the ability to efficiently handle change requests from their customer airlines is a big advantage for manufacturers against their competitors [268]. Aircraft purchase orders often include some customized requests [115] that need to be implemented without inflating their costs too much. For this reason, most challenges in aircraft redesign are linked to its change management process [268].

Despite its high relevance in current industrial practices, focus of design researchers has been concentrated on improving original product developments than redesign process of existing products [175, 345]. According to Sferro et al., very few methods are developed for use in product redesign process [291] and most of its activities have been supported either inefficiently or not at all by available change management methods and tools [270]. It can be hypothesized that this lack of research interest is because product redesign is generally perceived as an interruption to production [134]. A conducted survey in several product companies showed that more than 60% of them believed that product changes should be avoided at any cost [166]. This very strong notion of design changes solely as a problem leads to the neglect of any efforts to improve their strategy and process, which unfortunately also ignores the competitive benefits that could be gained from their proper planning and management [316]. Wright provided an overview of change management field in [344] and concluded that topics regarding product changes were largely ignored in the academic world notwithstanding their recognized importance in the manufacturing industry.

Taking into account the above arguments, the focus of this dissertation is to develop, test and evaluate a methodology for strategic redesign process. It is intended to be a decision-making support for designers who are attempting to modify an existing product design. Instead of treating redesign efforts in similar fashion as normal design iterations, which is what most companies are doing, it is believed that several competitive advantages could be gained if manufacturers effectively plan and manage design changes prior to executing their product redesign process. In that respect, the proposed redesign method is infused with key elements of product change planning and management. The proposed method is focused on aircraft redesign process but it can be extended to general product redesigns. The following section describes the scope of this thesis work in accomplishing this main research goal.

1.2 Research Scope Definition

The role of product redesign approach in current market strategies is well-acknowledged [160] and this has been reflected by its high rate of process adoption [108]. Most products in market today are essentially a modified version of their predecessor [96, 117]. A study by Booz-Allen and Hamilton Inc. revealed that 44% of perceptively new products were improved from older ones [70] and in such cases, many solution principles, properties, functionalities, components and parts are being reused [142]. Design of American cars is an exemplary case to highlight this situation since 80% of their parts were reported to be always derived from previous designs [184, 242].

As argued, the shift to mass customization has raised the adoption of redesign practices and as a result, design changes become more prominent in product development process today. The general scope of this research encompasses cross elements of product redesign and change management processes, which explores underlying interrelationships between these two areas of design researches.

1.2.1 Engineering Changes in Product Redesign Process

Like original development, product redesign process includes tasks such as requirement identification, benchmarking, specification planning, product concept generation, product embodiment, prototyping and testing, and design for manufacturing [248]. Nonetheless, product redesign does not start from scratch [171]. Instead, it often begins with a reverse engineering step to identify baseline components structure and their interconnections [73] but this procedure is often skipped when proper baseline design documentation is already available [302]. The baseline design information is essential in providing a solid decision basis for its evolution path, whether its redesign is best pursued from its configuration, subsystem, component or parametric level [249].

An example product redesign framework is illustrated in Figure 3, which highlights three primary redesign approaches. Parametric redesign is achieved by optimizing parametric product model without changing its design composition. It is essentially an optimization problem rather than a design problem, which is executed only after all required adaptive or original redesign plans are established [249]. On the other hand, adaptive redesign will modify product components or subassemblies but its original design concept is preserved. In this case, new components might be added and existing ones might be eliminated or combined. Last but not least, original redesign introduces a new product concept that is constructed from known design principles and knowledge of past product variations. It is pursued when new requirements are in serious conflicts with current product capabilities.

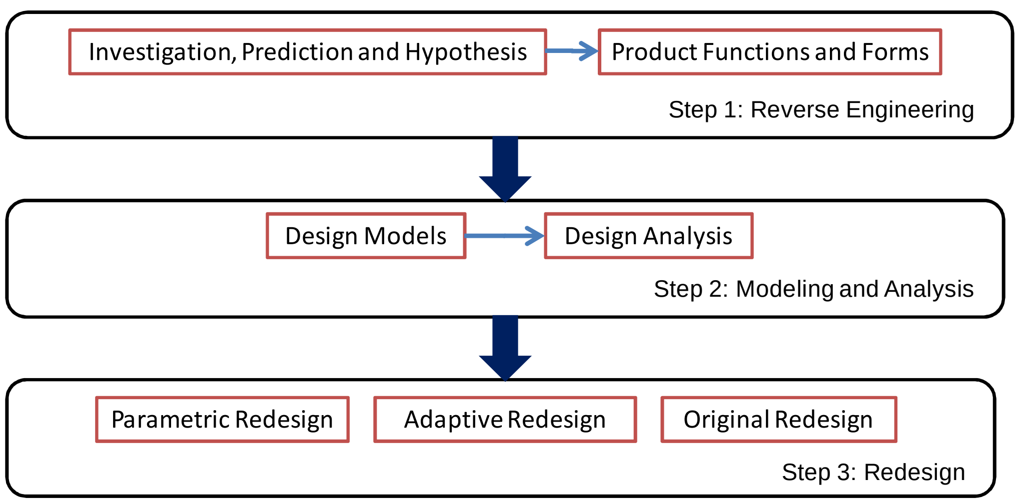

Figure 3: General Redesign Process Framework [248]

Application of redesign procedure within the overall product development framework is shown in Figure 4. While most design researchers tend to assume that product design and development process ends when its detailed specification has been passed to production and marketing teams [174], the real process is often far from being ideal. As illustrated in Figure 4, potential needs for design changes throughout product lifecycle indicate that it might need to be redesigned further. Motivations behind these latter changes are usually related to dynamic market factors such as changing customer needs or competitive moves made by other competitors. It is good to note that redesign process can also be initiated during original product development and is not limited to derivative development.

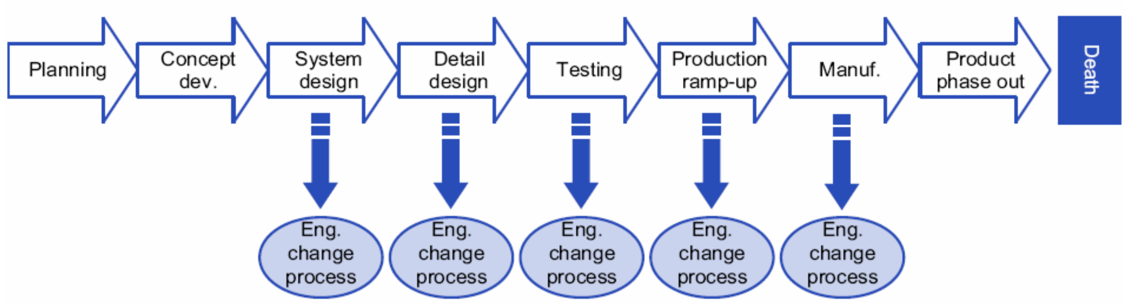

Figure 4: Engineering Change Process within Product Development [174]

It is apparent that redesign process involves making product changes. These changes are formally known as “engineering changes”, which by definition is any alteration made on a product or its component that can affect its form, fits, materials, dimensions, functions or documentation [166]. These include any revision of components, drawings or software that have been released throughout its entire lifecycle [321]. Engineering change is not to be confused with design iteration, which is defined as a change on product items that are not yet validated or formally released [265]. Based on this, engineering change effects are more pronounced since it occurs after some aspects of product design have already been specified and some parts of development resources have been allocated. The US Military Standard (MIL-STD-480B) classifies engineering change into Class I and Class II [10]. Class I refers to design modifications that can affect product physical configuration and functionalities such as its weight, performance specification, interfacing, reliability and safety [98]. Meanwhile, design changes in Class II category are associated with product configuration management that mainly involves documentation updates like amendments of design drawings and system description [98].

Since potential engineering changes are necessitated in various stages of product lifecycle and accordingly produce different effects [166], they can also be grouped based on their sources as either initiated or emergent. Initiated changes are caused by external sources to a product that are driven by its market dynamics [175]. These include modifications made to better meet its operational requirements and/or to improve its market competitiveness. In contrast, emergent changes are due to a product's state and they are required to remove or correct design weaknesses and/or to resolve design operational flaws [175]. Examples of initiated and emergent changes are depicted in Figure 5, which is based on helicopter development process in Westland Helicopters Company.

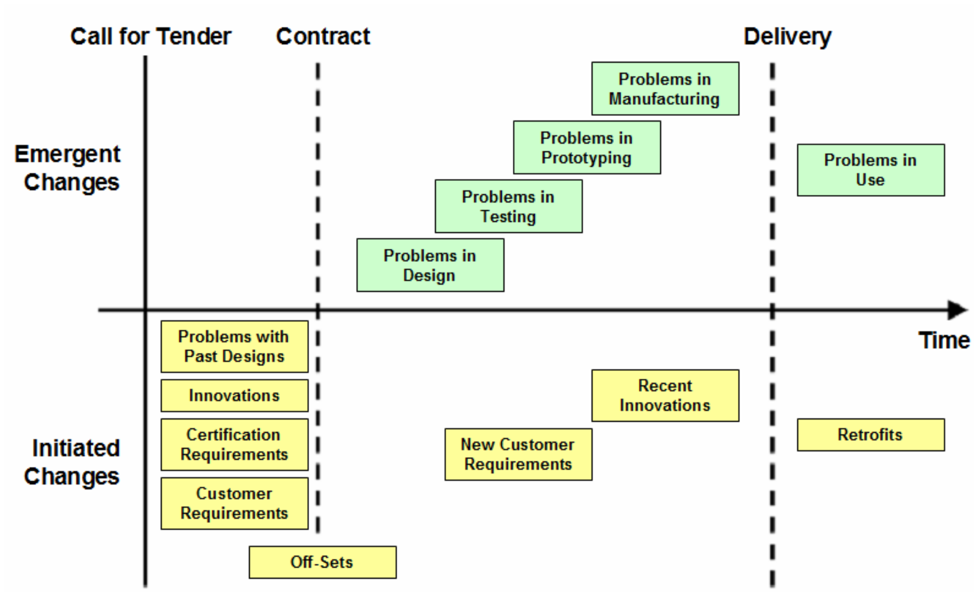

Figure 5: Initiated and Emergent Changes [115]

Change effects and their process efforts generally vary with time of handling [209, 321], type [273] and magnitude [193, 321]. In the best scenario, they only cause documentation amendments but in the worst case, they can stall entire production and force a recall on already delivered products [256]. Overall, change process contributes towards increased development costs and prolonged schedule delays [137, 176]. Documented studies based on several product companies show that change implementation process can consume up to half of their total engineering work capacity [301, 321] and is responsible for 20% to 50% of their overall tool costs [321]. In some extreme cases, as much as 70% to 80% of final product cost is contributed to engineering changes [71, 231]. A conducted survey in several American and European companies from defense, aerospace, consumer products, construction, electronics and a few other industries revealed that their difficulties to lower production costs were associated to their product change handlings that reportedly range between 2 to 1000 per month [54]. Since market success today highly depends on time-to-market, price and quality [242], it is important to have a good redesign strategy.

The vitality of a proper change management process to be competitive in current market environment is admitted by many manufacturers [321]. Majority of successful industrial organizations operates with a formal change process [190] and a survey on several UK product companies showed that 95% of them apply formal engineering change procedure in their operation [166]. As design changes rapidly become a prominent means for market survival, proper methods and tools to control their undesirable effects while upholding their offered advantages are required [160]. To do so, it is imperative to first understand change process characteristics.

1.2.2 Characteristics of Engineering Change Process

Engineering change management is a process of planning and managing product changes [174]. Its main objective is to outline all activities involved in monitoring and controlling of engineering changes [71, 190], which aids designers to plan for required changes and manage their implementation [25]. Fundamental properties of this process are change-independent and remains similar in spite of change causes and types [115]. An example of high-level procedure that is outlined by ISO10007 standard for managing engineering changes during product development is shown in Figure 6. Other change processes also generally follow a similar workflow but terminologies and strategies for each step might vary in different companies [176]. Most product companies tailor their own set of change tasks and management requirements to their organizational needs and work environment. Discussion of typical change activities is available by Huang and Mak in [165].

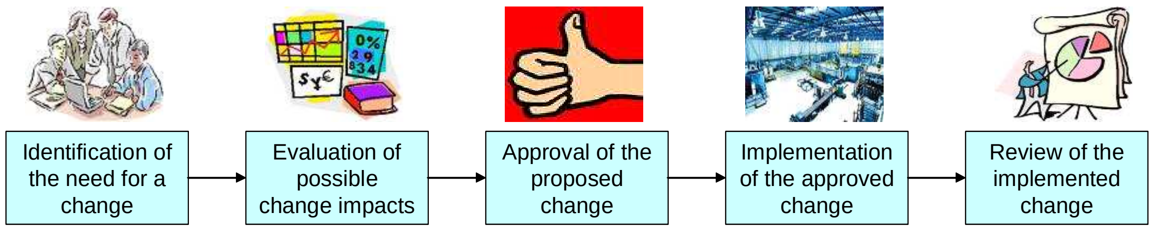

Figure 6: Change Management Workflow by ISO10007 [176]

In short, the process is started when an engineering change request (ECR) is initiated in response to new product requirement or change in company market strategy. Preliminary assessments on potential costs and benefits of the proposed modification are done prior to it being formally logged. Once it is officially documented, the change request is known as engineering change proposal (ECP). Each proposal will go through impact analysis and feasibility studies that determine its approval or rejection. If approved, an engineering change order (ECO) containing complete redesign plans and allocated resources for the product modification will be released and issued to affected personnel. A final review is done once the process is completed to document its details for future change support.

On the whole, it is evident that the outlined change process is very broad and serves only as a guideline for product manufacturers [273]. In reality, the "cause-change-effect" steps in change management are not entirely serial [137]. As evident in many product redesign cases, modification effects can propagate and create a network of interconnected changes [38]. Based on recent researches, Earl et al. summarized general characteristics of change process as follow [109]:

- Change takes place against a rich background of knowledge and experience embodied in a current product design, which is the starting point for change

- Change process is a fast moving, dynamic process, often highly creative in finding solutions
- Change processes work on descriptions of different design aspects such as function and geometry, available processes and resources, and requirements of the company, its suppliers and its customers

First of all, change process entails a well-defined baseline to be modified. It is impossible to describe an engineering change without its reference product design due to its relative nature. Secondly, change planning solution is usually not unique. There are often several ways to change an existing product depending on its redesign objectives and conditions. Lastly, product changes do not just affect its design but also its development process and associated business entities. One of the main process difficulties in redesigning a product is to capture its undesirable side effects [247], which affect other product characteristics apart from the targeted properties [314]. The effects can cross different boundaries within company's operation [127] as shown in Figure 7.

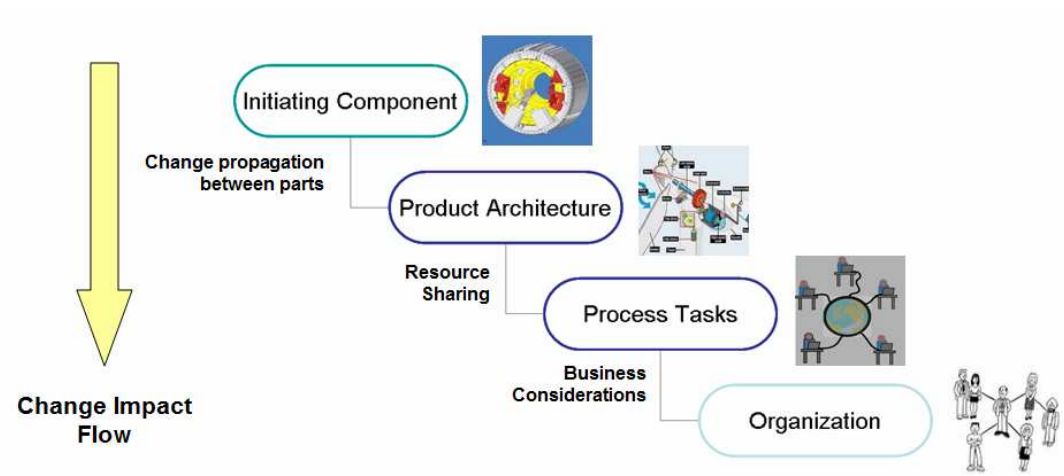

Figure 7: Typical Flow of Change Impacts [120]

In brief explanation, change effects are passed from initiating components to other parts through their physical or functional interfaces. To accommodate these changes, new or recurring development tasks have to be outlined. Since their execution typically involves information exchanges with existing tasks, this disrupts overall development process due to potential data revisions. Moreover, since those tasks are usually designated to different development teams or personnel, the change effects can be further felt throughout whole organization. In collaborative product development, this includes all associated business partners and suppliers.

Product architecture complexity has a big role in this “change propagation” phenomenon, where implementation of one engineering change drives several other changes [321]. Its possibility is dictated by level of connectivity between various product parts and a greater chance exists if they are highly interconnected [115]. Complex products such as aircraft are more susceptible to this phenomenon because connections between their constituent parts or subsystems cannot be totally avoided [295]. These intricate interlinks complicate the prediction of product behaviors during change process by introducing complex effects propagation paths that highly interact with each other [115]. This affects the budgets and scheduling constraints of product development process, mostly in an unexpected manner [267]. As depicted in Figure 8, change effects could be directly and indirectly transmitted through product architecture [265].

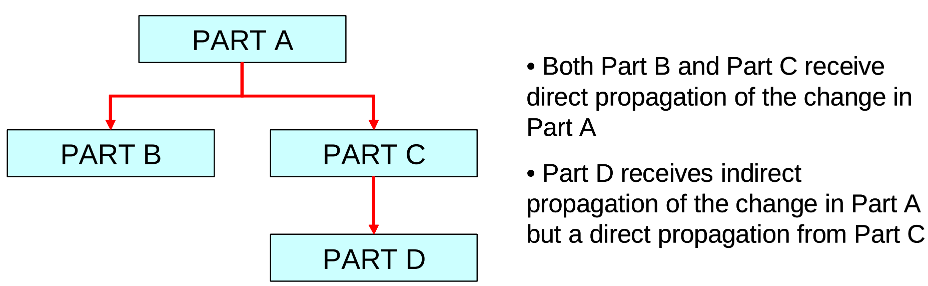

Figure 8: Propagation of Engineering Change Effects

Two types of change propagation: ending and unending [114] are illustrated in Figure 9. Blossoms and ripples are variants of ending change propagation, which are characterized by time-varying change volume that eventually concludes within an expected timeframe [265]. On contrary, avalanche is a type of unending change propagation. It occurs when a product change initiates several major changes such that their propagated effects become too hard to be resolved within allocated period [265]. It is crucial to control this second type of change propagation since its effects can easily grow out of proportion. A general rule of thumb is to search for alternative solution if the effects propagation is predicted to be unmanageable [115].

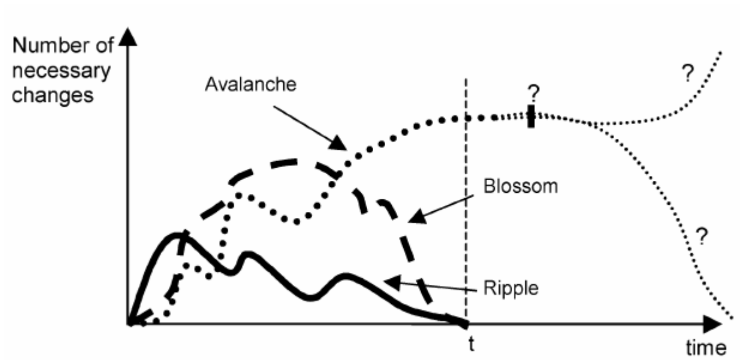

Figure 9: Types of Engineering Change Propagation [115]

Besides improving an existing product to its new requirements, another primary goal of product redesign process is to efficiently produce it [160]. A well-planned modification can minimize negative change effects and in several cases, even turn them into desirable benefits for the redesigned product [247]. Unfortunately, this is an overlooked viewpoint in current product development process [344]. At present, most product redesign process is executed in "as necessary" manner without proper strategic planning and its main focus has always been on "damage control" rather than product improvement [30]. An effective engineering change management for product redesign requires a thorough understanding of change behaviors and their propagated effects [134]. The ongoing lack of recognition for design change's influence in directing incremental or stepwise product development is a critical omission that has to be resolved given their prominence and effects on market success today [344].

1.2.3 Potential Benefits of Strategic Redesign

A general rule of thumb in product development known as "Rule of Ten" estimates that late design changes cost as much as 10 times higher than those made during early stages [65]. If engineering changes are executed later in product lifecycle such as during its full-scale production, design specifications have been detailed out and development costs and resources have been mostly committed [166]. Cost of change implementation also rises steadily as time approaches closer to pre-determined deadlines since the process becomes more time-critical and the product design becomes more integrated [115]. The projected trend for change handling cost is depicted in Figure 10, which exponentially increases as time progresses in product lifecycle. Moreover, change impacts are spread across other business processes when they occur after production has started [176]. Requirements for change notification and documentation updates are increased when marketing division, manufacturing teams, subcontractors, external suppliers and other work partners are also involved [174]. This affects the smoothness of the development process and lengthens its timeframe.

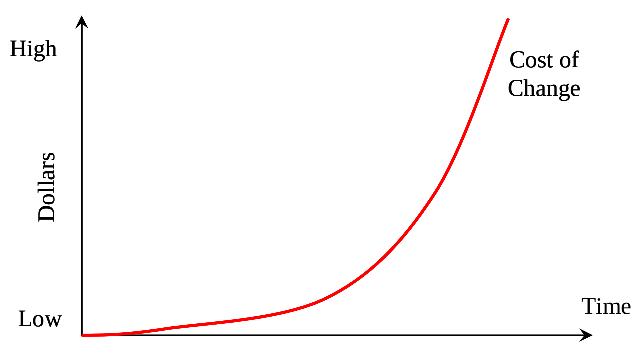

Figure 10: Cost versus Time for Engineering Change Handling [14]

From above arguments, late engineering changes have the most negative effects because they tend to cause higher additional costs and longer time delays [147, 210]. A simple but late washer replacement on a F-15 fighter, for instance, cost an astounding $56,000 [215]. That said, a considerable amount of development efforts and resources could have been saved if proper change assessment and planning strategy is made before making decisions on product modification [247]. Most opportunities for engineering changes are presented during early product development stages since effective redesign strategy helps to limit downstream change impacts and improve company's ability to deal with change requests from its customers [265].

Potential advantages of a strategic product redesign planning have been demonstrated by a few academically-developed methods. Cambridge Engineering Design Centre develops Change Prediction Method (CPM), which shows that better redesign risks assessment can be achieved by having more accurate prediction of change propagation paths [80]. With early knowledge of full effects from a proposed design modification, unexpected changes during product development are significantly reduced and better resources management can be accomplished. Another example method is RedesignIT by Ollinger and Stahovich, which highlights how a proper planning of product redesign can assist the management of change effects to achieve its performance targets [246]. In general, these change methods underscore the relationships between change management process and product redesign development, and their potential to provide manufacturers with notable advantages when applied in good synergy together. These two methods are further discussed in Chapter 3.

The need for a proper change assessment during early product redesign stages is aligned with ongoing design paradigm shift as illustrated in Figure 11. In short, the "knowledge-cost-freedom" curve highlights the preference to have more available product knowledge during early design phases, to maintain adequate design freedom throughout the process and to reduce overall committed costs, which are all functions of time [61]. This shift is driven by "design for affordability" and stresses on bringing product knowledge forward for better early design decisions [227].

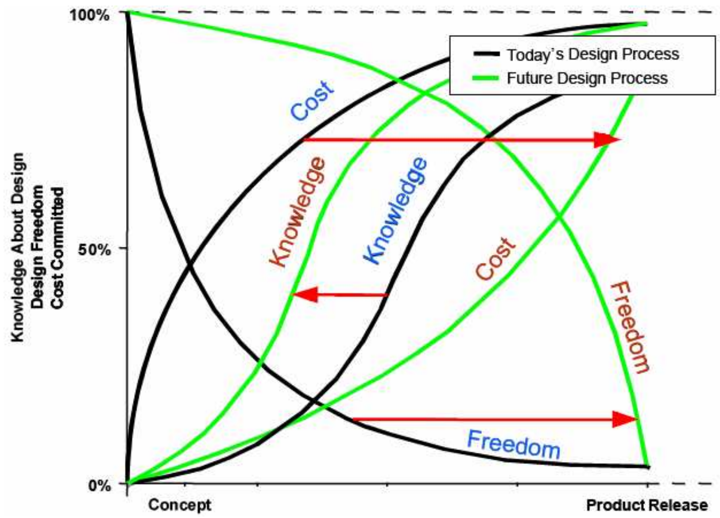

Figure 11: Paradigm Shift in Design Process [61]

In redesign process, the lack of early product knowledge is not an issue [62] but the main question is how available information can be appropriately exploited to make better early redesign decisions. Current natural tendency of many designers is to modify their product based on its targeted performances with "as necessary" manner and this outlook is largely shaped by available design methods that are developed for original product development. But unlike original development, product redesign is constricted by baseline flexibility, tighter budget and shorter development timeframe. If product redesign process costs and requires time as much as an original product development to satisfy similar requirements, manufacturer will be hard-pressed to justify that investment against usually higher market interest for originals. There is a need to support product redesign process in reaching for a well-planned solution that satisfies its driving requirements while making the most out of its allocated resources [314]. Product change proposals must be strategically planned and executed.

Without a good strategy during early redesign phases, change process can easily become mismanaged and trigger late changes due to overlooked problems with the product design or its manufacturing process. Some competitive drawbacks in automotive and aeronautics industries caused by a mismanaged change process are discussed in [267], which involve significant cost increments and prolonged development schedule [137, 176]. Almost half of product development projects in the early 1990's were reported to overrun their budget and scheduling time [56]. Such situation is often blamed on unexpected product changes that result from ineffective change management process [109]. However, several product companies are observed to still proficiently gain engineering change benefits despite their schedule conflicts and extra costs. Their operational element that contributes towards this advantage is their capability to have rapid and adept responses in managing their product changes [182, 273, 294]. A well-organized change management can help offset negative change effects with an efficient production of better and improved products [103]. In fact, agility of product manufacturing companies today is often measured by their competence in managing their engineering changes [168, 197].

To summarize, mismanaged engineering changes (hence a mismanaged product redesign process) often leads towards increased costs and prolonged schedule delays. These effects are more pronounced for late product changes, which explain the tendencies of current change strategies to minimize or eliminate them. However, since many required changes are driven by market challenges, avoiding them can also bring potential disadvantages to manufacturers. Though many manufacturers would like to avoid making changes to their products, they have to accept that some product changes are inevitable [115]. As market demands and requirements continue to evolve, product designs have to be improved at a potentially substantial cost and process disruption to remain competitively relevant in the new environment [125]. The next best situation is to have a good redesign strategy that minimizes negative change effects while providing its advantages to manufacturers.

Key Note: A well-managed product redesign process, hence a good change management strategy during the early development stages, can help reduce the negative effects of engineering changes and bring competitive advantages to the product manufacturers.

1.2.4 Current Gaps in Change Management for Product Redesign

In principle, engineering change handling in product redesign process is similar to that in original product development but its conditions are more constraining [270]. As change effects increase with time, product redesign efforts come with a higher impact since they occur at some point into its lifecycle. In addition, redesign process is commonly executed under tighter budget and time constraints, which create a higher requisite for an efficient change management procedure [120].

Current gaps in engineering change management for general product manufacturing can be contributed to attitudes of project managers and product designers towards change [30, 174]. They are more inclined to treat their product design change as a problem than as an opportunity for its evolution and tend to suppress them even when there is a great market value due to difficulties in capturing their full effects [264]. A conducted survey in 100 UK manufacturing companies revealed half of them considered engineering changes to be a primary problem in their product development [30] and accordingly, arising need for changes is seen as a sign of production failure instead of a process management issue that should be resolved [321]. Application of available change methods and tools are limited to eradicate product changes or to minimize future change impacts by incorporating high design flexibility into original products. None of these change handling approaches is an active method that can be applied when a required product change has been identified and needs to be implemented. Hence it can be concluded that the general competitive paucity of available change methods or tools is their incapability to effectively support and guide product redesign process [254].

Recall back the change process characteristics as previously mentioned [109]:

Characteristic 1: It requires a well-defined baseline to work on
Characteristic 2: Change implementation solution is not always unique
Characteristic 3: Implementation of engineering changes can affect more than just initiating change components or aspects

The main essence of an engineering change process is its baseline design. Working with existing or finished product designs, even at conceptual level, usually comes with less flexibility in terms of change implementation [115]. This relates to some constraints that are imposed by baseline product architecture and underlines the challenges in selecting a suitable design for adaptation or customization [117]. The importance of choosing a right baseline product in terms of its capability to be changed or adapted for the change tasks at hand has been emphasized by Pimmler and Eppinger [257], which generally requires an evolvable design to be effective [74]. A study has projected up to 80% of total design and manufacturing costs in a product development project could be dictated by such choice [343].

In current redesign projects, most baseline products are chosen based on their proximity to target requirements or because they are the natural choice for incremental progression in their product family [105]. This practice assumes that imminence of baseline capability to target requirements ensures minimum possible amount of required changes but this is not always true. Even closely similar components can have different level of complexity and cost for their manufacturing [110]. Therefore, baseline suitability should be reflected by its redesign cost-effectiveness and its required amount of reworks [178]. Furthermore, a smaller amount of required product changes does not automatically mean the redesign plan is easier or cheaper since that also depends on their type and magnitude. This insight leads to the first identified area of potential improvement.

Potential Improvement 1: A good baseline for product redesign process needs to have high-quality change characteristics with respect to proposed modification.

Secondly, there are often several different ways on how required engineering changes can be implemented into a product. Even for a similar set of requirements, several alternative redesign plans can be derived [309]. Because different parts can have very different level of change complexity and cost, the way a product is redesigned corresponds to a different level of change effects and development risks [25, 109]. Tu et al. said that the success of product mass customization depends on controlling its costs through proper development planning and process selection [324]. This draws attention to overlooked opportunities in change management field, which lacks strategies to decide how required changes are best realized into existing product architecture.

Fricke et al. discussed several current change strategies in [137] and the most common among them are change prevention and change front-loading [270, 286]. The prevention of product changes aims at avoiding design mistakes during early design conception. It is focused on correct translation of product requirements and reduction of needless product specifications that designers are forced to make without adequate information [137, 314]. Among research efforts that have been done in this area include knowledge-aided design for requirements management [203] and requirements management based on traceability and attributes [325]. System engineering standards like EIA 632 and ISO/IEC 15288 also aid the translation of customer needs into their associated product technical requirements

[148]. Alternatively, change front-loading involves early detection of possible sources for design changes to reduce their effects and costs [174]. By doing so, product changes can be handled during its early development stages and are prevented from becoming costly late changes. In this approach, risk management strategies are applied to control change risks [137], which are estimated using design simulation tools such as CATIA or methods that facilitate early validation and verification of design concepts like failure mode effect analysis (FMEA) or value analysis (VA) [137, 166].

Despite the abovementioned efforts, engineering changes still present in typical product development process [166, 270]. A reason for this situation is the inevitability of initiated changes. Eliminating or reducing design errors has no effects on market dynamics and it is quite impossible to control initiated changes due to irrepressible market factors. In fact, it is unwise to totally ignore them as they often reflect competitive product characteristics that are preferred by the market. It is good to note that not all change effects are negative. Design change allows designers to correct performance deficiencies of their product and improve its features against its competition [321]. When product requirements go beyond the capability of adopted solution principles, engineering change becomes the means to infuse novel ideas. Moreover, design change can be applied to gain market advantages in terms of scheduling; either to speed up product development process to gain first-in-the-market advantages or to compensate the current state of project resources [137]. In a fast moving business environment such as today, avoiding changes can be a serious obstacle to the evolution of product functions and technologies [138]. Based on these arguments, manufacturers should not be reluctant to redesign their products when the driving change requirements are important for their market competitiveness and associated development risks are manageable. Objectives of change strategies should not be limited to minimizing change likelihood but also reducing its implementation cost [201].

Corresponding to this realization, another main category of available change strategies is to equip original product designs with high changeability attributes in anticipation of their future changes [270]. Since the flexibility to generate a variety of product offerings from a single design resides principally with its architecture [326], objectives of this strategy are to furnish intended baseline designs with the ability to be changed easily and rapidly, and to be insensitive or adaptable to their varying environment [286]. It aims at deriving product variants in the most cost-optimized way when reacting to foreseen or unforeseen requirements for engineering changes [138, 277]. A baseline product can be developed to house predicted future changes in its original architecture, facilitate their implementation through pre-planned design options or be fully modified easily [272]. However, building products with high in-built design changeability considerably increases their development costs [67], as shown in Figure 12. Due to this disadvantage, not all product types suit this strategy and a basic guideline to evaluate product suitability for this approach is available in [308]. Examples of design methods that can be associated with this change strategy are product platforming and modular design.

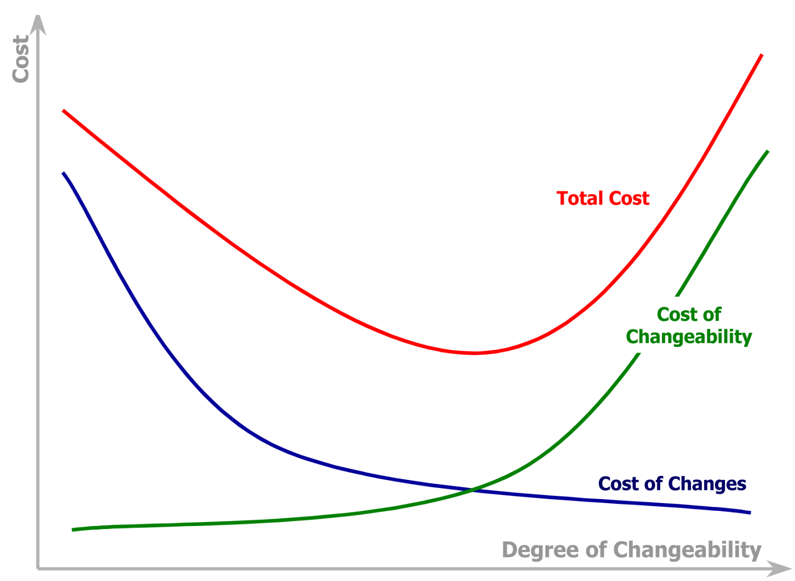

Figure 12: Degree of Changeability versus Cost [286]

A product platform is described as a common set of subsystems, components, interfaces, processes and other attributes shared by all design variants within a product family [234]. In product platforming, the main idea is not to design with definite number of variants but to make it easily modified for its future derivatives [117]. Accommodation of engineering changes is enabled on certain aspects of the platform design but its other characteristics are maintained for all its variants. This approach is recognized to support and ease change implementation process [280].

On the other hand, modular products are designed with distinctive physical modules [147, 252, 326] that are mapped one-to-one to their functions [241, 327]. This enables changes to be contained only within affected design modules without involving their interfaces or other modules [129, 175, 326] since they are basically de-coupled from each other [125]. Change management in this case is practically reduced to two typologies: “local changes” in the affected design modules and “interface changes” in the linkages between modules [175, 259]. Though design modularity provides the necessary flexibility that aids product mass customization [326], not all product types can be made modular with sensible costs and efforts [81]. In fact, most products are neither fully modular nor fully integrated [110, 175]. In addition to extra development costs and risks, and restricted applicability of this second category of change strategies, high market uncertainties also create difficulties to justify built-in design attributes based solely on manufacturers’ prediction.

To summarize, change prevention and front-loading, and high in-built design flexibility are adequate for stationary or slow-paced market environment. Their application however becomes fairly deficient when product requirements constantly vary over time [174, 314]. In today’s market, some requirements are adjusted during the detailed product design step [203] when these strategies are no longer applicable since they are meant to avert changes during the early development stages [184]. As for improving product design flexibility, it seems to be highly targeted for original development [272], which makes it unsuitable for redesign process. While these strategies have been proven useful in reducing changes due to designer's errors, a proper in-process change handling is also required [264]. Schmitt and Gomory argued that most US manufacturers tend to have long development cycle to research product market and avoid design changes that might not even there [285]. This differs from high-performance Japanese companies that put their products into the market faster to obtain first-in-the-market advantages and rapidly make necessary adjustments as their market evolves [320]. Changes that are driven by dynamic market factors could be "make or break" product features and manufacturers need to have a viable development strategy to manage their product changes [267]. However, current practices demonstrate a lack of understanding and appreciation on how engineering changes could be turned into market advantages [344]. The omission of any emphasis on change management during redesign process ignores its capacity to strategically drive the product development [166], which leads to the following second area of potential improvement.

Potential Improvement 2: A strategic redesign planning process can help manufacturers to gain change benefits without a big penalty of their effects.

In the meantime, a major advancement in engineering change management field has been made in computer-based support tools for its process execution [154, 270]. This is driven by compliance to industrial standards on product quality and process management such as ISO10007 and ISO9000 [109]. Traditional paper-based change management is naturally inefficient and slow [66, 157, 190], especially when serially executed throughout various departments in the company [66]. As product designs become more complicated, paper-based system grows to be incompetent in handling their subsequent alteration [175, 176]. Change implementation increases the amount of product data to be processed and makes it hard to manually maintain design updates. With progression in computing technology, most of these tasks have been converted into computer-based execution. Between 1980s to 1990s, several standalone and integrated computer aids for engineering change process have been developed [190] and they are classified into decision-making support, database storing, configuration management or product data management [165].

Decision-making support tools are aimed to assist product designers in approval process of proposed engineering changes. However, most of them do not capture the full extent of change process or its impact analysis [80, 115]. Capabilities of available computer-aided design (CAD) tools are usually not sufficient to realize the benefits of information reuse for redesign process [318]. Advanced CAD systems such as CATIA and ProEngineer can predict immediate geometrical behaviors but not other types of propagated change effects that result from product modification [80, 120, 259]. In contrast, computer-based change support tools to store historical product change data and process documentation are often built in-house [174] in relation to enterprise resource planning (ERP) or product lifecycle management (PLM) software packages [176, 344]. They compile all process records and product data across different phases of its lifecycle, including all past changes description [174, 316]. Their main application is to facilitate product data exchanges during change management process but they are not equipped to strategically guide designers in making the actual change implementation. Moreover, change support tools that are developed for configuration management are more focused on effective control of product information throughout its entire lifecycle [189]. They are meant for high-level documentation control and management of product design options but the actual process of making engineering changes is either ignored or covered by them in little depth [120, 174, 176, 278]. Last but not least, product data management (PDM) system essentially combines the functions of decision-making support and configuration management. Commercial packages such as IMAN, Metaphase 2 and Optegra are examples of PDM systems that cover entire product lifecycle [165, 190]. Among others, their main functions include product data vaulting, document management, part classification, production configuration, data conversion, workflow management and project management [251]. However, they are not equipped with capabilities beyond the linking of parts, processes and resources based on manual user judgment [120, 268]. In other words, they are simply a direct computerized version of conventional paper-based change management procedures [174, 268].

To sum up, most available change support tools are not equipped to guide or aid decision-making process in product redesign [120, 199] and they often can only record and track data related to past product changes [116, 176]. Additionally, due to traditional views of engineering changes as production-manufacturing issues [344], those available methods and tools only support change process after it has been initiated and production stage has began [175]. They are not intended to assist designers in predicting change effects while planning for product redesign but only to facilitate process execution and documentation that have been manually planned beforehand. In absence of proper change aids, current product redesign planning task is limited to listing likely affected design parts and related processes based on designers' past experiences. No strategic planning is formally infused into the process, which increases the possibility of overlooked change effects that have to be unexpectedly handled during late production stages [186]. A conducted case study in Westland Helicopters showed that about 50% of their total helicopter modifications were overlooked during its initial change assessment stage and had to be abruptly handled later in its development process when they were identified [81]. This solidifies the belief that available change tools and methods lack the critical element of strategic planning.

The use of computer-based tools in engineering change management is fast becoming an operational necessity for many manufacturers, especially those with a large scale product business [204]. Unfortunately, their application is presently limited to mostly information processing and documentation control [47]. An efficient change management process is only possible if change methods or tools are tailored to competitive product development strategies [267]. Amid high market competition today, personnel responsible for product changes have to be more than just an implementer [156] and able to strategically plan to the best capability of their company [113]. To date, no well-known ready-to-use software package that supports all aspects of change management process is available [259]. This should be perceived as a key absence given its established prominence, as highlighted in the following identified area of improvement.

Potential Improvement 3: Change support methods and tools should be equipped with capability to guide designers in making the strategically best change implementation decisions.

On top of these observations, it should also be noted that there are limited researches that address the supports for change management process in product development [166, 270]. Engineering change topics have garnered little attention notwithstanding their recognized importance in product manufacturing industry [316], which is unfortunate considering the potential market opportunities that they could provide to manufacturers. Current product change strategies need an implementation planning strategy and an expanded application scope to cover the key challenges in product redesign. Despite a small amount of research efforts in engineering change field, all of them highlight existing needs that support the relevance of this thesis study.

1.2.5 Scope Limitations

The scope of product redesign and engineering change management processes has been discussed in preceding sections. In this study, some limitations are applied to its problem scope to better refine its focus. This section is intended to detail out these limitations to avoid any confusion with the research work to be presented later in this thesis. In brief, they are derived based on aircraft redesign process, considered engineering change types and intended application capacity of the proposed methodology.

First of all, the proposed method is tailored to aircraft redesign process. Though for most parts the procedures are similar to other product types, their level of details and extent of decision-making are adapted for products with such a high design complexity. For simple products, decisions are usually made at their component level where the modification is directly applied but for complex products such as aircraft, involvement of many business partners and suppliers makes it hard for their primary manufacturers to always decide on that detailed level. In view of this, aircraft redesign decisions are commonly made at its subsystem level than its actual components. It can be noted that a typical aircraft system design has millions of parts. The MD-11 commercial transport aircraft, for instance, has about 184,000 different parts for its numerous subsystems [333]. In spite of the decision complexity, it is important for main aircraft manufacturers to identify engineering change effects that can propagate between major components of their aircraft subsystem. Many opportunities currently exist for innovation in quality and productivity aspects of aircraft redesign practices [239], and accommodation of this condition drives the construction of steps in the proposed method. It should be noted that requirements analysis procedure for the aircraft redesign is not included in this study since the proposed method assumes that this has been completed prior to its initiation and the list of change initiating components (and their proposed modification) has been supplied to engineering teams responsible for their implementation planning into the product. Further narrowing of the research scope due to this focus on aircraft redesign process is discussed in next chapter.

Secondly, from the standpoint of engineering design research community, “redesign” can have different meanings [68]. While the core of the procedures remains similar, which is making changes to an existing product, their objective and time of execution can lead to different interpretation. Three main types of redesign process are defined based on their handling time in the product lifecycle: during original design, after original design period or during reconstruction of original product [270]. The focused redesign problem in this study is to take an existing aircraft design and modify it to satisfy new requirements that are imposed on its next derivative, which is related to the last redesign process category. In contrast, the first category of redesign process is related to the handling of engineering changes during original aircraft development while the second is associated with aircraft modification during or after its original design has made its way to manufacturing floor. Hence for the interested redesign case in this thesis study, the baseline aircraft design has been well-defined and available degree of freedom for the redesign process is constricted by its existing flexibility. The rationale for this decision is discussed as follows.

The shift in market environment has led to shortened product lifecycle [196] and this also translates into a time decrease for manufacturers to competitively process their required engineering changes [40, 250, 348]. It is imperative to successfully conclude the product design projects on time to assure their financial viability and long-term competitiveness [113]. Despite such time pressure however, typical process lead time in reported product change studies still vary between several weeks to a year, with value-added time as low as 8.5% [48, 316]. In general, this long processing time is attributed to complex approval process, scarce capacity and congestion, set-ups and batching, organizational issues and “snowballing” of change effects [321]. Despite the efforts of design researches that focus on resolving intensive data requirements, high time consumption, change data access and impact prediction [165, 344], the same problem still persist. This leads to a strong belief that change process lead times can only be improved if a proper change implementation planning is done upfront of the redesign development process. In view of this notion, this research is focused on supporting change process that occurs during early redesign stages to highlight overlooked benefits of redesign change planning. Based on “strategic design” definition by Seepersad et al. [287], the proposed redesign method can be described as a marriage of strategic methods for leveraging and adapting existing products, procedures for assessing and infusing necessary design innovations, and systematic evaluations for comparing and selecting the best redesign plan among a portfolio of change alternatives. Accordingly, this means that engineering changes considered in this study are those that arise during conceptual and preliminary product redesign stages. It is not the focus of the proposed method to handle changes like design retrofits that occur after the production stage has started or while the aircraft is already in operation.

In addition, it is known that the form of engineering changes ranges from physical design alteration to documentation update to software maintenance. From previous discussion of available methods and tools, management of product documentation has been covered in the development of computer-based change support tools while software maintenance has been captured by researches in software management field. Physical product changes, on the other hand, are lacking proper focus in current change management process. Although these various forms of changes are tackled separately, they can be easily interconnected to one another. For instance, each physical product change automatically signifies a need to revise its related documentation [270]. Hence the proposed redesign method is focused on planning physical engineering changes and it is assumed that their information can be routinely extended to the company’s product documentation database.

Last but not least, most manufacturing companies adopt a customized engineering change management process that is tailored to their organizational needs and strategies. As stated by O’Donovan et al., the range of interests and views for product design process makes it hard for a single method to capture various interests and practices [244]. Accordingly, the key problem for commercially available computer-based change support tools is typically linked to their generalized change procedure that is made to increase their applicability in companies from diverse industrial backgrounds. However, this makes them unsuitable for application in detailed product redesign process. British Aerospace developed their own change management software because the required efforts to refine available commercial packages to suit their organizational needs are perceived as too taxing for them. Their customized engineering change management package is described in [190]. Taking this into account, it makes more sense to develop the proposed method in support of existing change processes than as their total replacement.

While time delays caused by inefficiencies of adopted change methods, tools or working environment are difficult to improve without affecting the entire company's organization, change processing time can be minimized by eliminating or reducing process iterations. In previous Figure 6, engineering change itself is iterative in nature as it goes through its review and approval stages [71]. Loch and Terwiesch offered a structural map of adopted change process in actual product company in Figure 13.

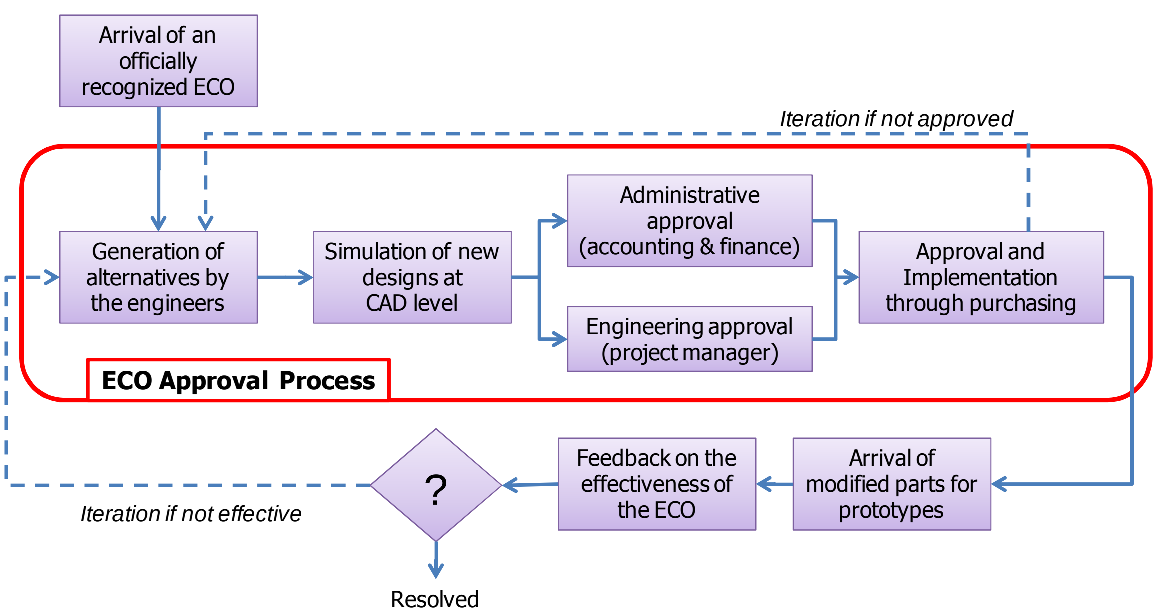

Figure 13: Engineering Change Process Example [210]

From Figure 13, change process require iterations when the proposed modification is not approved for implementation or when the problems still remain after the product has been modified. A proposed product modification is rejected if it is assessed to be too risky and remaining problems after modification are commonly due to misinterpreted requirements or unaccounted change effects by the proposed change plan [174].

A good change proposal helps to reduce process iteration by ensuring a high possibility that the requirements can be met by the proposed product modification and having all its side effects pre-determined in its specification. A good change planning includes accurate identification of its implementation tasks and effective allocation of available resources [111]. As decision-making process is often the “bottleneck” point in change management procedure [316], availability of these details helps to smooth out the process. In fact, a lot of time can be saved within overall product redesign development if several competitive change implementation options are simultaneously generated. Instead of having to restart redesign planning for each change process iteration, available backup plans can be used in cases when the first chosen plan is disapproved [243].

Thus far, it is apparent that the main potential room for improvement is to support present change management process with means to generate competitive change proposals. This entails a good change implementation planning strategy to screen out infeasible proposals based on their possible impacts of change propagation [185, 270] while complementing the depth of product designers’ experiences [115]. In view of this, the proposed method is focused on supporting existing change management process by aiding product designers in generating good change proposal plans based on their redesign objectives.

Key note: Summarized scope limitations for this study are listed as follows:

1. The proposed methodology is tailored to the aircraft redesign process.
2. This study does not include change requirements analysis for the aircraft redesign.
3. The application of the proposed methodology is intended for the conceptual or preliminary phases of the reconstruction of an existing baseline product.
4. The main focus on the proposed methodology is the planning of the physical product engineering changes.
5. The proposed methodology is intended to support the existing formal change management process by being an efficient change decision-making aid to generate competitive change implementation plans.

1.3 Research Objectives

The urgent needs to improve product redesign process have been sufficiently established and the scope of this study has been clarified in previous section. In short, this research is narrowed down to the formulation of an engineering change planning method for product redesign approach, which is applied prior to the initiation of formal engineering change management process in the manufacturing company. The major output from this method is a set of engineering change proposals for any well-defined initiating product changes. It should be emphasized that the proposed methodology is meant to be a change decision-making aid and not an automated change plan generator. This is amply summarized in the following purpose statement for this thesis.

The purpose of this thesis is to develop a methodology that supports decision-making process in product redesign through efficient engineering change implementation planning

In corroboration with the above work intent, several research objectives are set up based on current gaps in product redesign methods and underlining characteristics of change management process. It should be noted that these research objectives are in parallel with suggestions from several primary engineering change literatures such as Eckert, Pulm and Jarratt [117], Rouibah and Caskey [270] and Eckert, Clarkson and Zanker [115].

Research Objective 1: Reduce risks of product redesign process by incorporating changeability assessment on baseline design in early stages

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Research Objective 2: Improve identification of potential change effects by incorporating analysis of direct and indirect change propagation

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Research Objective 3: Improve product change implementation planning by aiding designers in defining appropriate change solution space and supporting their change decision-making process

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Research Objective 4: Reduce costs and time delays of product redesign process by generating competitive change implementation proposals

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1.4 Thesis Organization

Overall structure for this thesis documentation is depicted in Figure 14. This first chapter has built the case for relevance of this research by explaining its motivation and pressing industrial needs. In addition, the study scope has been outlined by defining its limitations and research objectives that guides development of proposed method. Chapter 2 describes current aircraft redesign process that is the central focus of this thesis study. It discusses the challenges in aircraft development process, which further shape required steps for the proposed method. Chapter 3 reports upon extensive literature review to identify available tools and methods to close identified gaps in aircraft redesign practices. Based on gained knowledge, research questions and hypotheses for this study are presented in Chapter 4. Proposed methodology to address research questions is also described within this chapter, along with an Excel-based computer program to support its application. Next, Chapter 5 explores research questions and hypotheses through two implementation case studies of notional aircraft redesign using proposed method. This thesis concludes with Chapter 6, which contains final discussion on this research work and suggested future work.

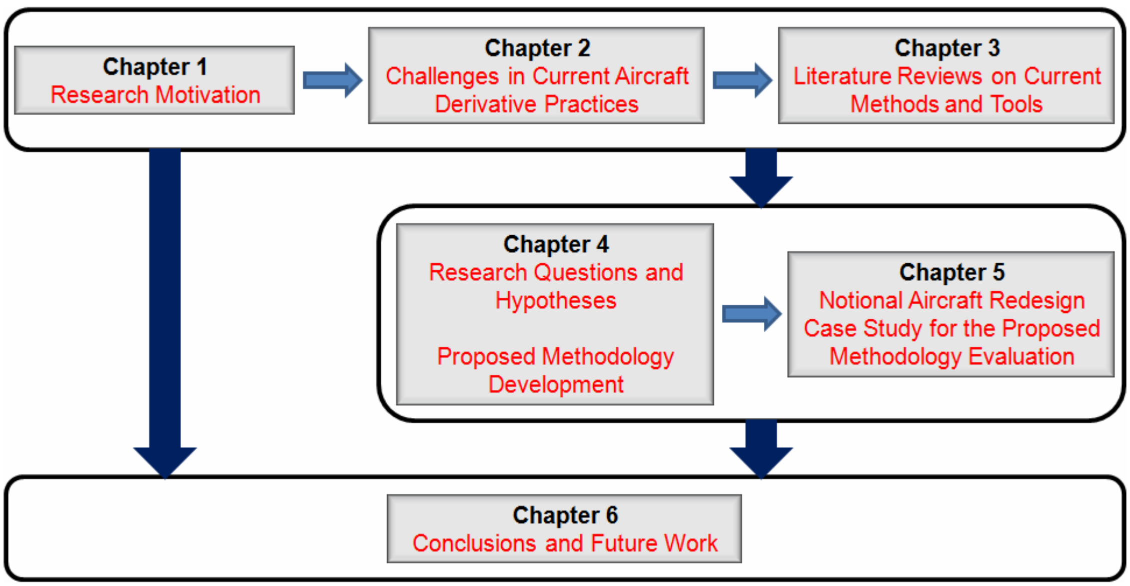


Figure 14: Thesis Organization

1.5 Chapter Summary

The progressive shift of product marketplace towards a customer-driven environment has increased its dynamics. In product manufacturing industry, this leads to changing mindset from traditional mass production to mass customization. This is to cope with rising needs for manufacturers to improve product's quality, functionality and features while reducing its costs and shorten its time to market [318]. Prominence of product redesign approaches and engineering changes is becoming more pronounced. It is common to perceive present product development as a continuous change management process [137], which involves substantial redesigning and administrative efforts that can be reduced only if it is well-managed [259]. Despite acknowledgement of their significant effects on product success today, potential for having a strategic redesign planning is still largely been ignored by many manufacturers.

At present, redesign approach is focused on eliminating late product changes or build-in high design flexibility into original products to absorb their expected future changes. This is primarily due to attitudes of product engineers and design managers, who view changes more as a problem rather than an opportunity to improve their product competitiveness. As evident in many product development cases, even experienced downstream engineers cannot totally avoid late changes [337]. In addition, while many change implementation proposals appear deceptively simple [109], they are associated with level of complexity that influences their required amount of efforts and process completion timeframe [112]. Available change methods and tools are limited and inadequate to deal with challenges of dynamic market environment today. In several case studies, improperly planned redesign changes have been shown to negatively affect the product development process [111] and this strengthens the belief that current change processes are usually mismanaged. This situation needs to be properly addressed since market success today is greatly dependent on product's time-to-market, price and quality, which are significantly affected by a poor redesign planning [242].

In particular, the main overlooked aspect of product redesign process is the planning of its proposed modification. As demonstrated in several academic research works, notable competitive benefits could be gained by manufacturers if they spent more time planning their product's initiating modification [76, 321]. This notion is the primary motivation for this thesis work to develop a strategic product redesign methodology.

CHAPTER 2

DERIVATIVE AIRCRAFT DEVELOPMENT

"*An efficient control of engineering changes at the development stage is strategic for aircraft manufacturers*."

- Riviere, Feru and Tollenaere (2003)

As stated in previous chapter, the focus of this study is on derivative aircraft development process. This chapter is intended to offer essential background of current aircraft redesign strategies. In the first section, eminence of aircraft redesign practices and their relevance to current market challenges are highlighted. Typical aircraft development process is also described within this section. In the second section, main challenges of aircraft redesign process due to engineering changes are recognized and associated with identified areas of improvement. This chapter concludes with the tailoring of steps for the proposed aircraft redesign method based on gained knowledge so far.

2.1 Aircraft Development Practices

An aircraft is one of the most complex, technology-based, engineered systems [141]. Its design and development process is a daunting task since it is not just a system performing some specified functions but also a revenue generator for its operators: the airlines [220]. Very few product industries can match the volatility of aircraft industry where numerous external factors can contribute to its market dynamics. Systems Engineering Application Technical Committee in the International Council on Systems Engineering (INCOSE) has outlined five main external factors that contribute towards aircraft system environment as illustrated in Figure 15.

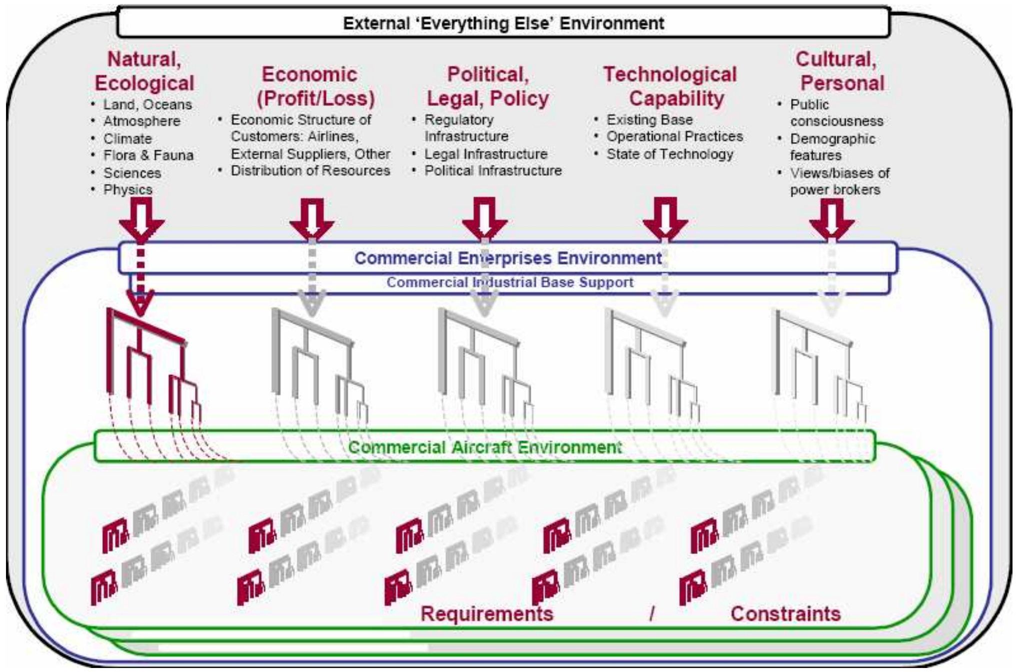


Figure 15: Primary Factors for Commercial Aircraft Environment [15]

In general, commercial transport aircraft market is split into two main segments based on design capacity. The first market sector corresponds to aircraft systems with more than 100-passenger capacity while the second accommodates those with less than that, which are mostly business and regional types [266]. Airbus and Boeing are currently the leading aircraft manufacturers in the world and they have a market duopoly in the 100+ capacity segment [319]. The second market segment, on the other hand, is mostly being served by various regional manufacturers [255]. For both market segments, derivative development has been a prominent approach in aircraft manufacturing. Between 1980's to late 1990's, only five original designs were introduced into large commercial aircraft market. Boeing produced their original B757, B767 and B777 aircraft while Airbus had their A320 and A330/340 designs [86]. As depicted in Figure 16, the market during that time period was filled with more than 20 derivative aircraft [86].

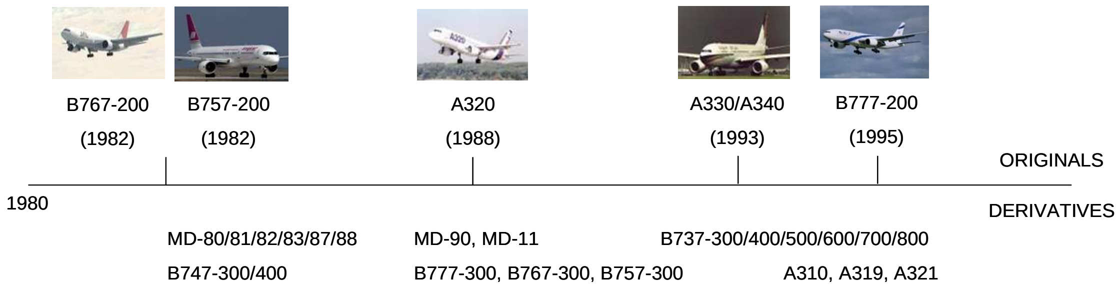


Figure 16: Previous Aircraft Development Timeline

Over the last few decades, the aerospace market has progressively changed. Many aircraft manufacturers struggle to survive the market that is characterized by drastically shortened production cycle, intensified fierce global competition and increased product variety and complexity [331]. The marketplace demands more customization and this leads to more engineering changes being introduced during development process [267]. Because a new aircraft development usually takes more than five years, it is highly infeasible to develop individualized design for each customer airline. It is more common to exploit available flexibility within existing aircraft designs to implement the customized options. Based on Utterback's industrial innovation model, the current aerospace industry can be considered to be in "*specific phase*" with well-established dominant designs, in which most market opportunities exist in incremental improvements instead of revolutionary product designs [239, 328].

2.1.1 The Significance of Aircraft Derivatives

According to Dassault Aviation, the twin business challenges for aircraft manufacturers today are to design and develop technologically sophisticated aircraft with affordable cost and in a shorter timeframe [50]. Due to high competition in commercial aviation industry, manufacturers are pressured to reduce their aircraft development risks [262]. In view of this, advantages of aircraft redesign approach make it more favorable than building new original aircraft. Besides cheaper and faster to develop, derivative aircraft also feature an improved performance at a lower risk and their commonalities to their predecessors can help avoid significant increase in airlines' maintenance and operational costs [86]. During initial development plan for Boeing's B747X planes, their production cost was to be kept down by reusing existing components and factory tooling of B747-400 aircraft [58]. This highlights potential savings of costs and resources by derivative development. Moreover, another attractive element of derivative aircraft is their design certification. Unlike a new original aircraft design that is subject to rigorous safety requirements, derivative aircraft could avoid such stringent certification process. Without major design changes that can affect the safety level of its predecessor, it can benefit from past certification of the latter. Boeing B737-800 aircraft, for instance, can carry up to nine extra passengers than Airbus A320 of similar operational class because of its predecessor's exit doors and emergency evacuation certification, although the latter complied with a higher safety standard [86].

In the meantime, new technologies are not the most appealing factor to airlines [20, 87]. Due to high operational risk of air transportation business, airlines are more keen to have high reliability of matured technologies than to cope with extra risks of new ones [116]. This is evident from lukewarm market response that greeted Airbus A320 aircraft, which was seen as too revolutionary when it was first introduced into the market due to its fly-by-wire (FBW) flight controls and composite structures. It took almost two decades later for these technologies to be fully accepted by the market [20]. This demonstrates that big investment on new original design with too many revolutionary technologies could also be counter-productive and risky for aircraft manufacturers. In contrast, airlines respond better when technologies are progressively infused into existing aircraft once they have matured and accepted by mass market [89]. Plus, without the needs to demonstrate and validate new technologies in their aircraft offerings, manufacturers can avoid prolonging their development program for as much as five extra years [240].

As shown in Figure 17, Boeing has practiced incremental upgrade strategy in their B737, B747, B757 and B767 aircraft programs [258]. It can be observed that prevalent redesign approaches in aircraft manufacturing are product platforming and family modeling [107], both of which follow evolutionary or incremental progress of existing designs [84].

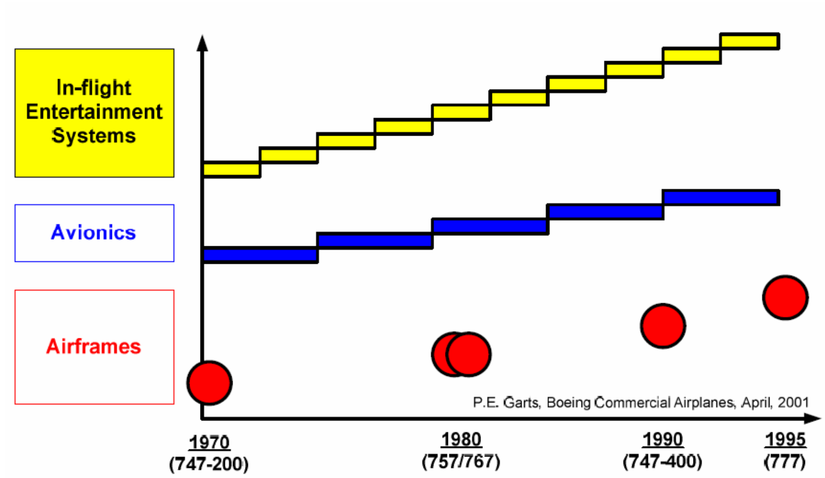


Figure 17: Relative System Upgrades on Boeing Aircraft [125]

In product platforming or module-based redesign approaches, a derivative aircraft can be developed by adding, removing or substituting one or more modules in its baseline design [296]. Despite the changes, the redesigned aircraft mostly retains the basic architecture of its baseline. Boeing has long practiced this strategy, which is apparent by observing their derivative aircraft series. For instance, even after more than 30 years of its first flight, the original B737-100 aircraft design is still visible in its derivative B737-700 [127]. In each derivative progression, new subsystem technologies are often phased in to extend design applicability in newly-changed market environment [86, 316]. Overall, the key advantage of this incremental derivative strategy is its ability to develop a perceptively new aircraft in a shorter timeframe and with significantly reduced efforts as compared to starting from scratch. By upgrading aircraft subsystems with newly available technologies, its market relevance is prolonged and its competitiveness is maintained.

On the other hand, in family modeling or scale-based redesign, architecture of each future variant in the aircraft family is developed as a package within a single common baseline [128]. It involves systematic planning of modularity and commonality for physical and functional aspects of each product family member [107]. From airlines' point of view, an aircraft design is often measured by its capacity and range [88, 266] and for that reason, derivative aircraft family is developed by adjusting baseline design based on its range-payload relationship. While keeping as much subsystems commonality as possible with other members of the aircraft family, payload capacity of derivative aircraft is reduced to increase its operational range and vice versa [86]. This concept is illustrated in Figure 18. It can be noted that most derivatives are often derived through shortening or stretching of their baseline aircraft [296].

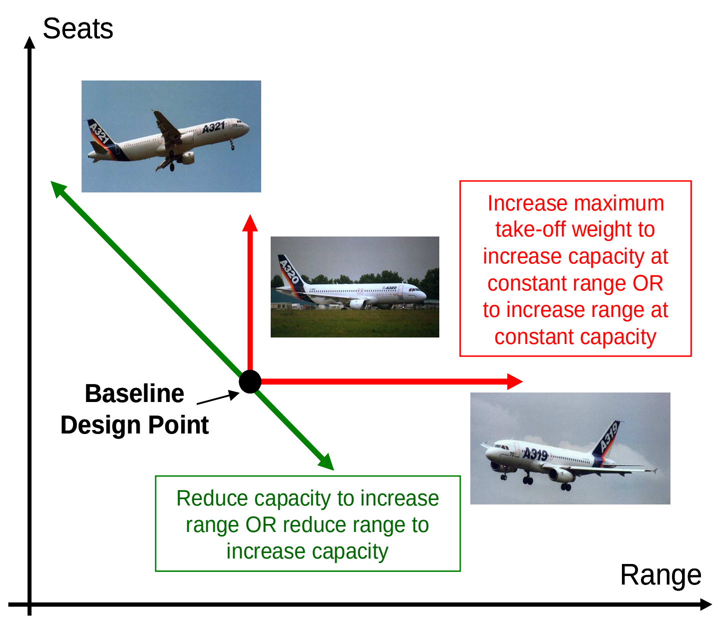


Figure 18: Development of Derivative Aircraft Family [86]

Airbus has capitalized on this derivative strategy since their introduction into the large commercial aircraft market. This approach enables a faster development of wide range of aircraft offerings, which greatly helped them to cover broad range of the aircraft market spectrum in shorter timeframe. As the latest market entrant at that time, this capability is instrumental for their survival against established aircraft manufacturers like Boeing and then-McDonnell Douglas [85]. Thus far, aircraft families produced by Airbus are based on three designs: Airbus A300 in early 1970's (baseline for A300-600 and A310), Airbus A320 in mid-1980's (baseline for A318, A319, A320 and A321) and Airbus A340/330 in early 1990's [85]. By using this family-oriented approach, Airbus is able to provide more flexibility to their customers to switch orders from one capacity module to another within the same aircraft family until time of delivery without much cost penalties owing to their inherent commonality features [303]. This is very appealing to airlines and a competitive move that is not able to be effectively offered by incremental development approach [20].

It is important to note that this derivative strategy is not based on an existing design. An original aircraft design has to be developed as a main baseline for future derivatives in a family. This is usually perceived by airlines as simultaneous development of several new aircraft instead of simple reuse of old design elements and principles. Airbus has enjoyed high interests that are typically associated with novel aircraft developments for each of their derivative markets by developing only one new design. Nonetheless, this also means that the process starts off like an original aircraft development and has relatively higher risks and costs than step-by-step derivative approach [58]. The ongoing development of Airbus A350 can be used to demonstrate this condition. By changing its plan from being a direct incremental derivative of A330 aircraft to an original baseline design for eventual A350-800 and A350-900 derivatives, its market entry was pushed back four years behind initial market introduction of its rival: Boeing 787 [90] and its total development cost is projected to top $15 billion [223], which is significantly higher as compared to a typical incremental derivative.

To summarize, derivative strategy has a big role for aircraft manufacturers in maintaining their market competitiveness. Murman et al. predicted that derivative configurations will continue to dominate commercial aircraft systems market [239]. Both aircraft platforming and family modeling strategies offer their own advantages that are relevant with current market challenges, especially in coping with growing customization trend where original aircraft development is not a viable option. In addition, ability of aircraft manufacturers to address change requests from customer airlines as early as during negotiation process is key to their market competitiveness [268]. A study in Westland Helicopters revealed that 10% to 15% of their helicopter redesign costs occurred before the sales contract was signed, which were generally spent on planning required design changes and estimating their full effects [81]. This puts further emphasis on efficiency of redesign planning that can only be achieved if the change management process is executed in good synergy with aircraft development process.

2.1.2 Aircraft Development Process

Aircraft design and development is unquestionably a very complex process. John Leahy, the Airbus sales chief, echoed this sentiment while commenting on production delays that have affected both Airbus and Boeing companies in their current A380 and B787 aircraft development, respectively [223]. The shift in aircraft market environment towards a more customer-driven setting has forced a rethinking and restructuring of its long-established development process. In general, traditional aircraft design and development framework (shown in Figure 19) has been adapted into a customer-driven quality process in Figure 20. This shift is in parallel with other product industries, where "*many companies have come to realize that the key to world-competitive products lies in high-quality product design*" [102]. Instead of sole focus on performances, aircraft manufacturers today has to design for "*affordability*" where main challenges are associated with development costs and manufacturing process [284].

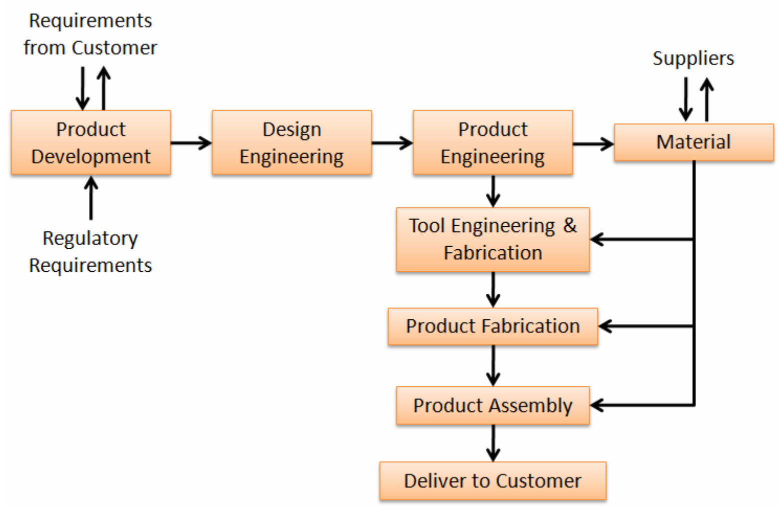


Figure 19: Traditional Aircraft Development Process [214]

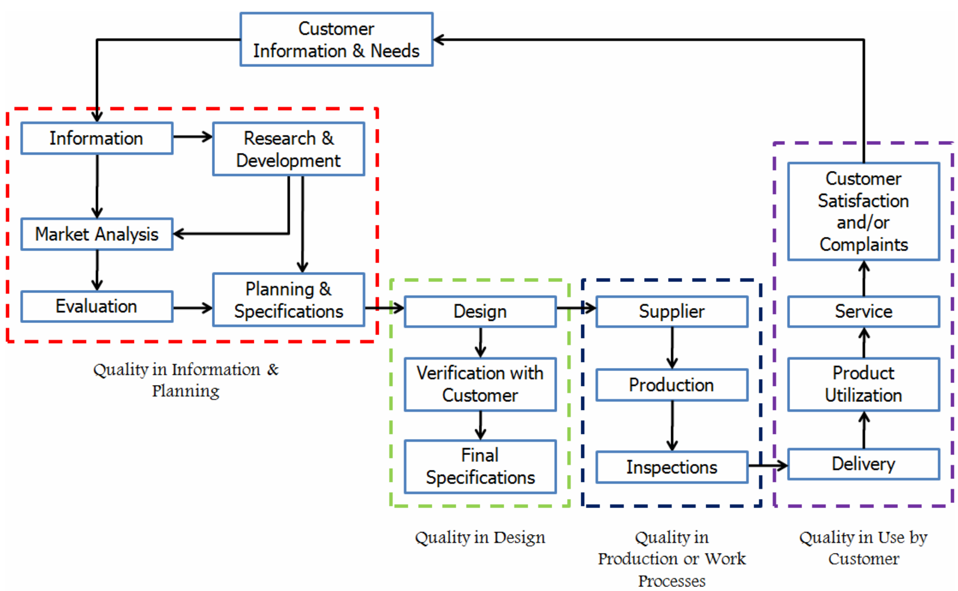


Figure 20: Quality Planning in Aerospace Manufacturing [214]

The scope of this study can be associated with the "*quality in information and planning*" phase in Figure 20, specifically "*design planning and specifications*" tasks. Main output from this phase is a documentation of planned design specification [214], which is similar to an engineering change proposal for redesign process. Though the framework in Figure 20 is focused on original development, aircraft redesign process can be perceived as its subset due to their shared design and development tasks [33]. Many engineering changes during original aircraft development occur before its proposed design gets to production floor [268]. For instance, amid their received criticisms for proposed A350 aircraft design as a direct derivative of A330, Airbus redesigned the aircraft before it was later approved for development and production [24, 90]. It took a whole year and at least four definition reworks before the redesigned A350 proposal was released [89]. This shows that redesign process can occur during original aircraft design and development process and is not only limited to derivative development. Note that in this thesis work, redesign process of “new original aircraft” is termed together with derivative aircraft development.

Like other product industries, aircraft development process involves identification of its requirements, listing of tasks to accomplish the work, and identification and allocation of required resources for its successful execution [212]. Design process of an aircraft system prior to its production stages can be decomposed into three phases: conceptual design, preliminary design and detailed design, which are traditionally executed in that sequential order. In short, conceptual design results in a feasible aircraft concept that is tailored to the established driving requirements, which is refined through higher fidelity analyses in preliminary design before a complete specification is finalized in detailed design stage. An example process is illustrated in Figure 21. A main challenge to design an aircraft is its multi-disciplinary nature. This is characterized by degrees of influences that one of its design disciplines has on others, such as how aerodynamic lift and yaw moments drive the sizing of horizontal stabilizer and rudder, which in turn affect flight controls system [262]. In his discussion on flight control system development for Boeing B777 aircraft, McWha acknowledged how interdependent aircraft subsystems are and how crucial it is to consider the overall system integration during its design process [233]. The situation is more problematic when early design decisions are made with very little hard information about these interactions [62].

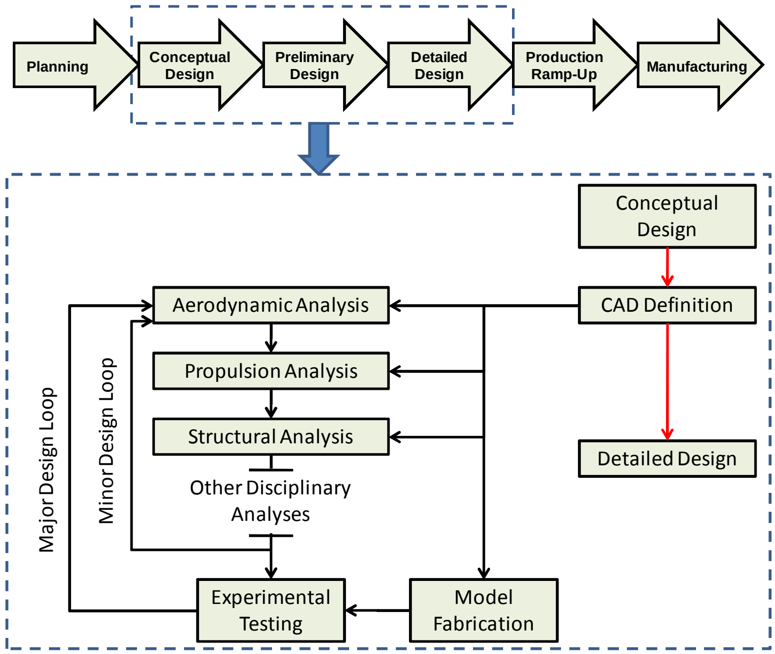


Figure 21: Aircraft Design Process [262]

In Figure 22, while high level concept and requirements for main aircraft subsystems are decided during conceptual stage or early preliminary step, their interactions are seriously considered only during the detailed design stage. If the early decisions are found to be mismatched at this later point of development process, the aircraft design will be brought back to its analysis stages once the required design changes to remedy the situation have been proposed. In general, this 'top-down' development strategy puts enormous pressure on designers' ability to correctly conceptualize detailed aircraft design in the early stages with very limited knowledge of its final subsystems [31].

For products with high design complexity, it is a common practice to outsource some of its development aspects to various sub-contractors or suppliers [71, 270]. Most aerospace products today are produced by outsourcing as much as 70% of their design elements to different suppliers [130]. For instance, 70% of activities in Airbus A380 development are carried out by a network of sub-contractors that involves about 39 companies [31, 266].

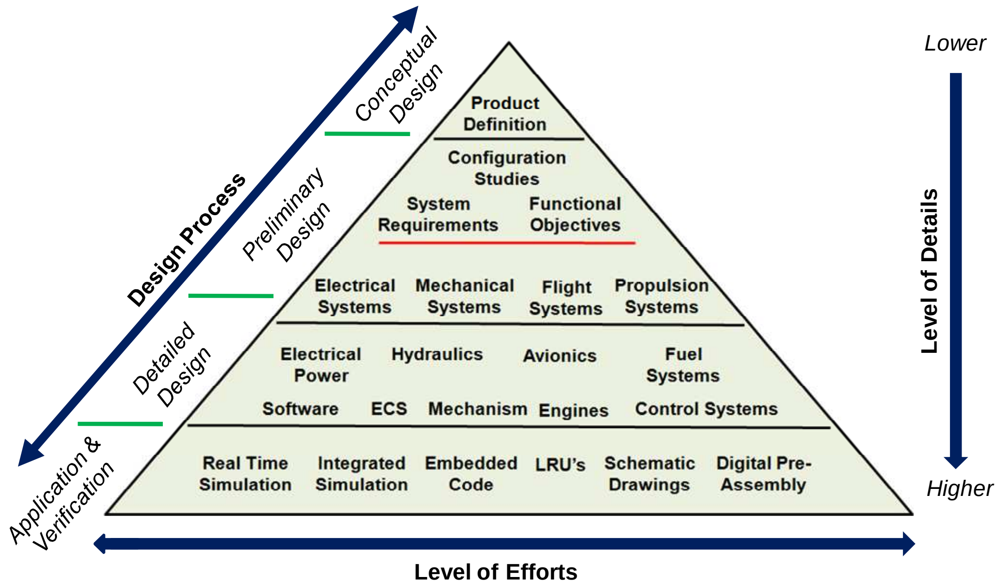


Figure 22: Boeing's Systems Design Environment [31]

Although this "work sharing" strategy reduces risks for primary aircraft manufacturers, it results in a scrupulous change management process that poses as another big challenge in aircraft manufacturing [176]. Recent problems with their suppliers during the production phase have delayed Boeing B787 aircraft almost 14 months behind its initial schedule and Airbus has already lost almost six billion dollars of profits with production problems of their A380 aircraft [224]. This highlights the essentiality of good coordination between different parties involved. Table 2 lists out the hierarchy of suppliers in aircraft industry.

Table 2: Categories of Companies in Aircraft Development Process [31, 266]

Category	Description
Prime Contractors	Main airframe manufacturers such as Boeing and Airbus that are responsible for design and final aircraft system integration
Tier 1 Suppliers	System manufacturers that are responsible for design and development of complete aircraft primary subsystems
Tier 2 Suppliers	Suppliers of main equipments for Tier 1 companies to develop primary subsystems – usually do not involve in any research and development activities
Tier 3 Suppliers	Supplier companies of low capacity that works with Tier 1 and Tier 2 companies but not directly with prime contractors

To deal with these aircraft design and development issues, several concurrent engineering (CE) methods and techniques have been introduced over the years [253]. The main goal of CE approaches is to bring more design constraints that are used to be considered later to the early stages where conceptual decisions are made [105, 196]. This enables a better coordination between aircraft design and its manufacturing process [155], and improves the communication between various business partners and suppliers [174, 316]. Potential benefits offered by CE methods in aircraft redesign are evident in Airbus A340-500/600 derivative development, in which an estimated reduction of 25% development time and 30% costs (equivalent to a saving of about 50 million Euros) are reported in comparison to basic A340 development [253, 266]. In relation to engineering changes, making good decisions during conceptual stage is a significant step towards eliminating the needs for expensive late changes. CE approaches such as Integrated Product/Process Development (IPPD) have been demonstrated to reduce the amount of late design changes in aerospace product development [227], as highlighted in Figure 23.

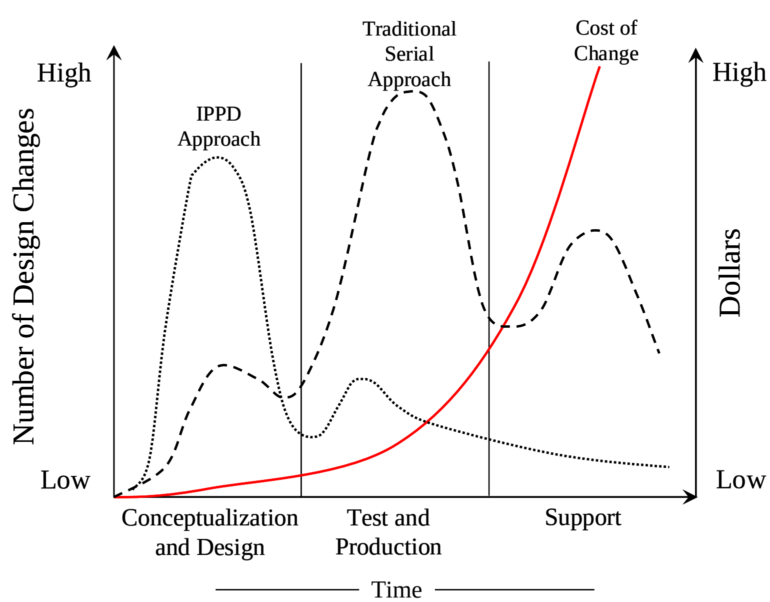


Figure 23: Comparison between Traditional Serial Design and IPPD Approaches [14]

Although CE efforts improve early decision-making process and enable smoother product information flow [214], issues of design changes largely remain in aircraft development process. They target efficient execution of design and development process, which focus on preventing or reducing emergent changes due to decision-making or communication errors [32], but they offer little help to aircraft designers when it comes to actual change implementation. In addition, many aircraft manufacturers are more inclined to regard the need for changes during their development cycle as a problem instead of an opportunity for their product evolution [266]. This underlines the lack of appreciation for engineering changes among aircraft manufacturers as their potential competitive means. Despite this negative attitude, manufacturers do concede that an efficient change management during their development process is an issue that influences their product and organization [268]. Boeing, for instance, encountered a necessary redesign of a critical part in B787 aircraft when it was already on the assembly line [224]. This is an exemplary case to demonstrate that engineering changes still occur even with the application of CE methods. Without the backing of a proper redesign strategy and support, such process can prolong development downtime that cannot be afforded by aircraft manufacturers. In the case of Boeing B787, its wing redesign forced a month-long downtime that cost some of its competitiveness against rival Airbus A350 aircraft [29].

Several industrial standards related to engineering change management that are relevant to aircraft manufacturing including ISO 10007, RG AERO 00023, MIL-HDBK-61B and ANSI/EIA 649 [273] only offer generic change process outlines. None of them suggests any change impact analysis methods despite emphasizing the importance of such process [273]. Robert Goussault, the Vice President of Information Systems Division at Dassault Aviation, commented: "*when a modification is made, the impact on the design has to be considered very quickly. You have to be able to make the design changes in days rather than weeks, and in weeks rather than months*" [50]. From this statement, the challenges of engineering changes in aircraft redesign process are closely related to the efficiency of manufacturers in identifying causes of change and evaluating its impacts on their product, process and organization [267].

2.2 Engineering Change Challenges in Aircraft Redesign Process

Redesign process of complex products is rarely straightforward and is highly susceptible to problems of change propagation [79]. For one redesign case in Westland Helicopters Company, initial design changes to add a forward looking infrared radar (FLIR) turret on their helicopter design ended up causing modifications to its avionics, fuselage structure and nose cap, power supply, cabling and piping [81]. To date, several studies have been done to identify causing factors of design changes in aerospace industry, such as Riviere for commercial aircraft development [266] and Hsu et al. for military aerospace programs [164]. Among identified change factors in the aerospace industry are listed as follows:

- Changes in market needs and product requirements
- Interactions between simultaneous development programs or phases
- Identification of product flaws due to design errors
- Advancement of new technologies and obsolescence of current ones
- Changes in governing regulations
- Changes in business strategies or scheduling

The presence of engineering changes in aircraft development for both commercial and military applications should always be expected. Clarkson et al. stressed the importance of a good change management procedure for complex products due to the high magnitude of their change effects. Interviewed engineers in Westland Helicopters commented that each kilogram of additional weight from implemented design changes cost them almost $25,000 and unexpected late changes in their helicopter redesign averagely cost as much as five times higher than if they were handled during early stages [81]. The fact that most engineering changes in aircraft derivative development are initiated during early redesign phases should have been to the manufacturers' advantages. With available information about its baseline aircraft design, a good redesign strategy can help to assess proposed change effects and provide market advantages to manufacturers by eliminating necessary reworks in later stages. But in current aerospace industry, these design changes are often linked to negative performance effects, prolonged development activities and significant cost increments, which can be blamed on lack of efficiency and responsiveness of many aerospace companies in their change handling process [267]. Clarkson et al. stated that current industry lacks a clear approach in predicting and representing change propagation phenomenon, and is too dependent on product experts to manually minimize its effects [79].

There is no doubt that the advancement of aircraft subsystems for commercial transport is outpacing the changes made at its system level [44]. Learning from Boeing's problems in their B787 production, Airbus recognized the importance of efficient change handling at subsystems level by enabling more times and design involvement to their sub-contractors before production of their A350 aircraft is started [224]. If any subsystem deviates from its initial specifications, proper assessment of change effects propagation has to be made to identify other affected subsystems. The potential to increase the efficiency of change management for aircraft redesign process lies mainly in capturing overall change effects propagation at subsystems level. But with current 'top-down' subsystems development approach, many system engineers find it difficult to predict how their proposed change effects can propagate to other subsystems and what other required modifications should be expected [229].

2.2.1 "Top-Down" Aircraft Subsystems Development

An overview of aircraft development process is illustrated in Figure 24. As depicted in the figure, aircraft subsystems development starts once the overall aircraft system concept is chosen but before its complete specification is detailed out. This is one of the accepted traditional rules for a good aircraft development policy, which is to provide a clear idea to contractors about the expected role of their subsystems without specifying in details how they must look and perform [153]. However, it is apparent that simultaneous subsystems development by various subcontractors will challenge the precision of task division made by aircraft manufacturers [266].

Within competitive concurrent design engineering and development environment today, aircraft manufacturers make early outsourcing decisions of their subsystems development to distribute risks and costs, and to garner the best contractors' skills and competencies to their advantages [284]. Because aircraft subsystems will be independently developed and optimized according to specifications in their technical and contractual definition [63], it is important for aircraft manufacturers to thoroughly consider the effects of any proposed redesign before providing such details to their designated sub-contractors and suppliers. Although initial contract definition often specifies preliminary installation space volumes and expected subsystem performances, it is not until much later that the actual details can be finalized by sub-contractors through their own system development process [266]. If there is a deviation from initial concept, manufacturers have to assess subsequent impacts and update other affected subsystem contractors. The failure to efficiently do so may lead to expensive reworks during final assembly. Design reworks for Boeing B787 aircraft on its assembly line have delayed its market launch by almost 14 months [29] and increased Boeing's research and development spending to almost three billion dollars to keep the program on track [106]. Such negative effects have a big impact on manufacturers' image and their market competitiveness.

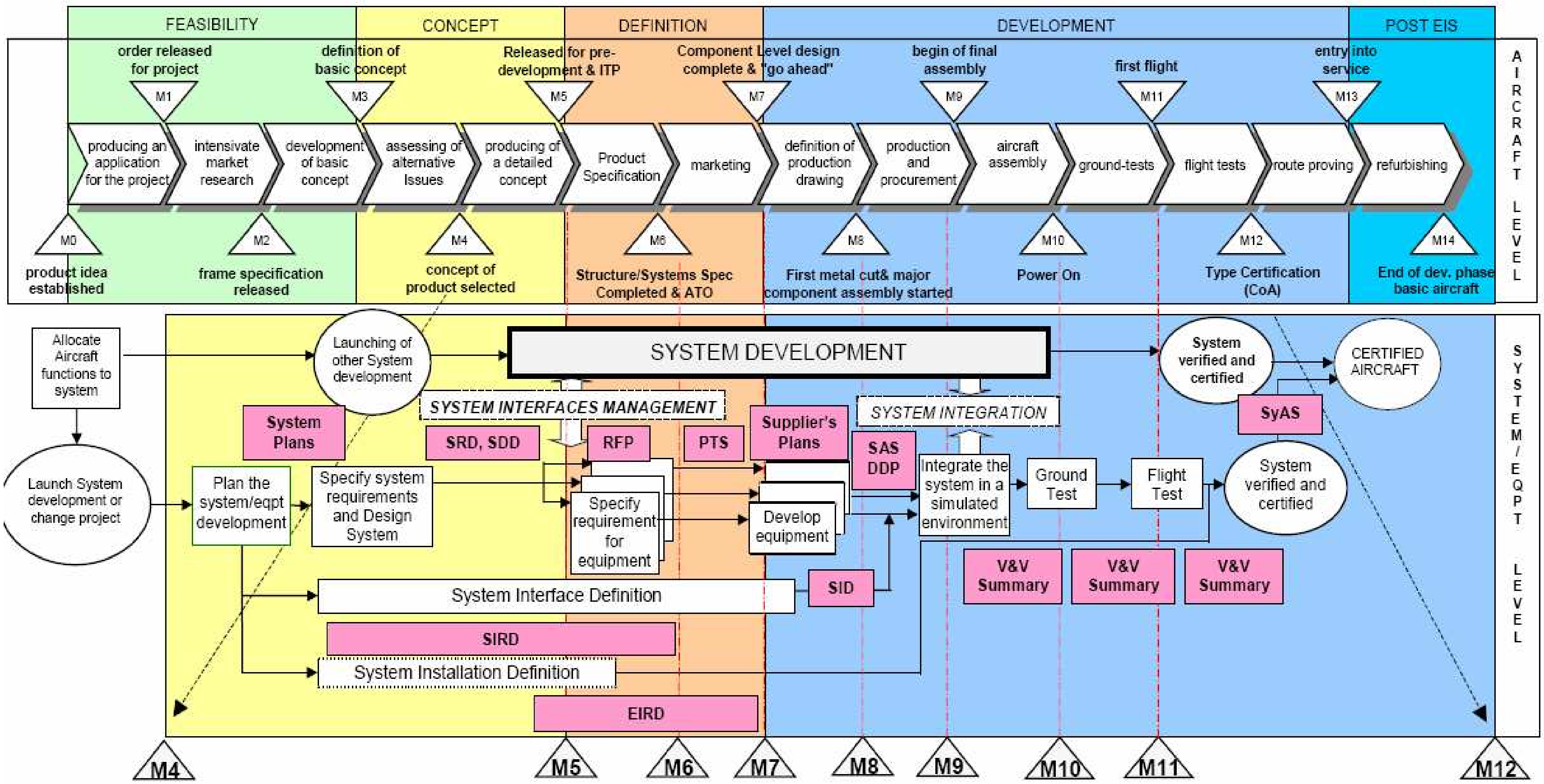


Figure 24: Aircraft and System Development at Airbus [33]

Table 3: Aircraft Development Process Milestones at Airbus [266]

Milestone	Summarized Description
M0 to M2	• Identification of market needs for a new aircraft design
M2 to M4	• Selection and optimization of design concepts for the initial configuration of the new aircraft
M4 to M5	• Definition of task sharing for the aircraft subsystems sub-contractors
M5 to M7	• Finalization of the aircraft design specifications and cost-performance analysis for development "go ahead" approval • Contract finalization with the launched customer airlines
M7 to M8	• Initialization of the aircraft manufacturing process
M8 to M11	• Manufacturing of the aircraft components, final assembly and testing
M11 to M13	• Flight test and aircraft certification

An example of task overview for aircraft manufacturers in overseeing their subsystems development process is illustrated in Figure 25.

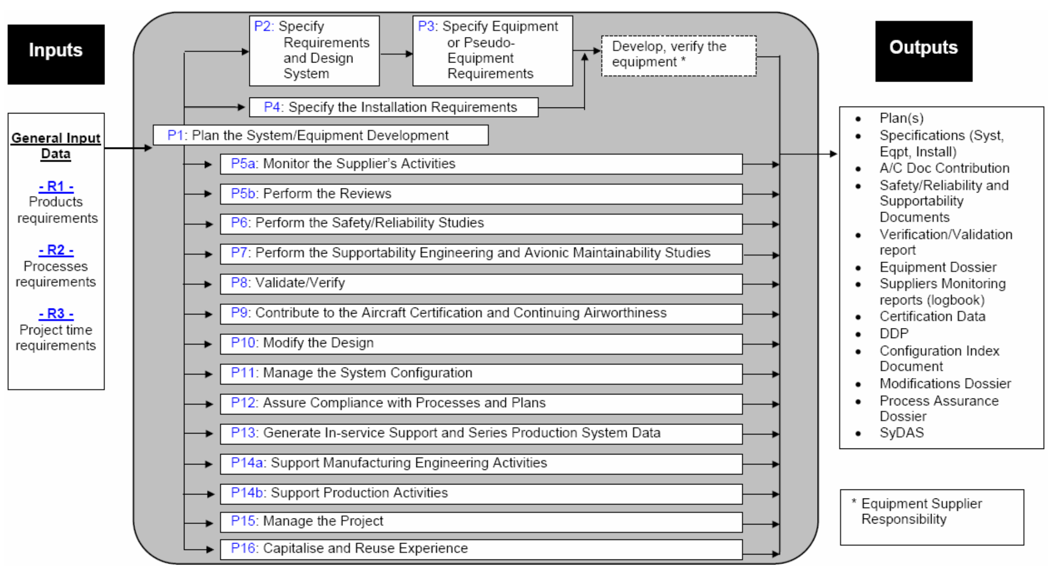


Figure 25: Overview of Subsystem Development Process in Airbus [33]

High design complexity of an aircraft indicates that its parts are interdependent such that a modification on one part may affect others [43]. To have a better depiction of proposed change effects on one subsystem to another, these interlinks must be identified. However, common "top-down" development approach in which subsystems design is determined by target aircraft performances often ignores any feedbacks to system level and hence to other subsystems [229]. During initial conceptual design, subsystems are assumed to be able to accomplish any operational requirements that are imposed on them by decisions made at aircraft system level without creating new constraints themselves [229, 262] but no such guarantee exists. There is a clear danger that decisions are made solely based on top system level metrics [181] and mismatches between subsystems will induce several reworks in later development stages. For instance, if the redesigned aircraft subsystems are aimed to be more electrical-based, then higher-capacity electrical generators may be required. However, installation of these generators may require a bigger volumetric space than initially prescribed, which imposes modification to airframe structure. Traditionally, system designers only hope that additive effects of subsystems integration will not affect overall aircraft requirements and performance goals, and falls within design tolerances that are incorporated in initial design specifications [63]. However, as reported in many product development projects, there are "*many stories on how a seemingly innocuous change blossomed into a series of costly impacts*" [264].

Unlike original aircraft development that is started from scratch, aircraft redesign process has the luxury of more detailed information available on its baseline design specification. Instead of just hoping for everything to fall into places, aircraft system designers can use this knowledge to track and estimate change impacts earlier in the process or to predict possible reworks due to their redesign plan. Subsystems interdependencies require that any proposed redesign plans to consider them simultaneously to avoid a "*redesign chain reaction*" [243]. Proper understanding of feedback and cross-subsystem constraints can prevent costly changes late in the design process and provide guidance in the evaluation of architecture alternatives [229].

2.2.2 A Better Aircraft Redesign Planning

So far, it has been argued that problems with engineering changes during aircraft redesign process can be attributed to lack of consideration for interrelationships that exist between its different subsystems. With as many as two millions parts in each aircraft design, their coordination could not be any more important [253]. Based on an empirical case study of Trent 800 aircraft engine at Rolls Royce, systemic nature of interactions between its sub-components has been shown to complicate overall aircraft design process. Instead of just "*requirements pass down*", development of this subsystem imposes "*definitions pass up*" flow that can possibly lead to a few large-scale system redesigns [243]. This underlines the needs for sufficient knowledge regarding baseline subsystems interconnection before proposing any design changes to it.

To further emphasize this matter, observations made in Westland Helicopters, the world leader in rotorcraft design, are listed as follow [79]:

- Designers often fail to realize how their design decisions will affect others
- Several knock-on changes occur during redesign process, resulting in changes typically no more than 4 steps removed from the initial change
- Estimates of total unexpected changes ranged from 5% to 50% of total amount of modifications made in each redesign case

Without any change management aids, the responsibility is left on designers to manually plan product redesigns. In most companies, this often translates into tremendous reliance on senior design staffs to remember all past changes and to be able to mentally track them quickly when required [176]. Under market environment today, demands and pressures on designers to reduce lead times and to avoid costly revision are considerably increased [47, 304]. In many observed cases, they often fail to recognize the complete insinuations of their proposed changes, particularly in cases of complex products [38, 142]. Typical aircraft system has tens of thousands different parts that support hundreds of its diverse functions and they are integrated in various ways that create millions of potential change critical interconnections [185]. It is rather impossible to thoroughly understand such high system complexity and manually identify full engineering change effects on its elements, which are difficult to envisage once they cross boundaries between various subsystems [247]. In addition, it is rare for designers to have detailed knowledge about the complete product apart from the portion that they are responsible of [115]. This ultimately leads to situations where change process is executed without proper planning of their complete impacts [120, 259].

Aircraft redesign process can greatly benefit from the consolidation and reuse of design knowledge of its baseline [38]. This is acknowledged in the development of Memory for Initial Design of Aircraft Subsystems (MIDAS) tool, which is intended to support design process of utility subsystems during early aircraft development [105]. Though no further indication is available in the literature to suggest that this tool has been completed for full aircraft system design application; its concept supports that subsystems interconnections play a big role in aircraft redesign. Overall, observations of redesign challenges in aircraft manufacturing with regards to the potential areas of improvements identified in previous chapter are listed in Table 4.

It can be concluded that current aircraft redesign process shares similar lack of emphasis and strategy regarding management of engineering changes with other product industries. Although redesigning an existing product is usually perceived as a less challenging effort than developing an original product design, its outcome is no less important in securing market competitiveness for manufacturers. In environment of massive product adaptation today, it is very beneficial for manufacturers to have a viable redesign strategy that can be improved through design process researches [70]. Traditional methods of prevention and early prediction of design engineering changes are not enough to provide the best market competitiveness for manufacturers. Instead, their application needs to be augmented with an efficient change implementation strategy [264]. Next section discusses development of the proposed aircraft redesign method.

Table 4: Challenges of Engineering Changes in Aircraft Derivative Development

Area of Improvement	Observation in Aircraft Industry
A good baseline for product redesign has high-quality change characteristics with respect to the proposed modification	Common choice of aircraft baseline is made based on closest performances to target requirements and no serious consideration is made regarding its change effectiveness
A strategic redesign planning process helps manufacturers to gain offered change benefits without the penalty of its effects	Engineering changes encountered in aircraft development are often treated in "as necessary" manner and as a result, their effects have been mostly negative
Change support methods and tools should be equipped with capabilities to guide designers in making the strategically best change implementation decision	Most change management methods and tools that have been used in aircraft development process are more focused on data networking between various business partners but no redesign decision-making support is offered

2.3 Building a Methodology

The first step in constructing the proposed strategic aircraft redesign method is to identify available methods and tools that, when modified or used together, can effectively form the foundation for a better method. Based on state-of-the-art capabilities and potential areas of improvement recognized from previous observations in aircraft manufacturing industries, the application gaps between current methods and research objectives for this thesis study can be identified. This knowledge guides the formulation of steps for a better aircraft redesign process.

Research objectives outlined in previous chapter indicate that resultant change proposals from the proposed methodology should not only contain a good redesign plan but they also have to be planned in a way that suits the requirements of formal change process in the company. Therefore, this initial review is focused on extracting the main essences of process workflow in available product redesign and change management frameworks. Methods that are identified and discussed here are listed as follows:

1. Collaborative Management of Engineering Changes (CM-EC)
2. Parameter-based Engineering Change Management
3. Change Process Planning
4. Reverse Engineering and Redesign Methodology
5. "Anchoring and Adjustment" Redesign Strategy
6. "Design for Assembly"-based Product Redesign Approach

2.3.1 Collaborative Management of Engineering Changes (CM-EC)

For complex products such as aircraft, the goodness of their documentation is associated with that of adopted configuration management system by their manufacturers. In view of this situation for aircraft development process, Riviere proposed a methodology known as Collaborative Management of Engineering Changes (CM-EC) that effectively combines product configuration management and engineering change management processes [266]. However, instead of developing new change methods or tools to enhance its management process, this framework is more focused on improving global performance of the aircraft development process [267]. Its emphasis is on efficient data communication between all business partners, which is one of the key determinants for success or failure in a product development project [218]. In other words, its primary goal is to construct a cooperative environment for engineering change management process where everyone involved can access updated product information, share results, and use incorporated change analysis methods or tools to investigate change impacts and derive product change solution [268]. By accomplishing this, manufacturers' responsiveness in processing their product change requests is enhanced and its implementation process can be executed more efficiently by providing full control to configuration managers.

CM-EC process framework is shown in Figure 26, which is constructed based on studies in automotive and aeronautics industries. It is divided into three stages: change proposal, change investigation and change embodiment. The application of the proposed method in this thesis study fits into the change proposal step where change pre-feasibility studies are done for implementation planning analysis.

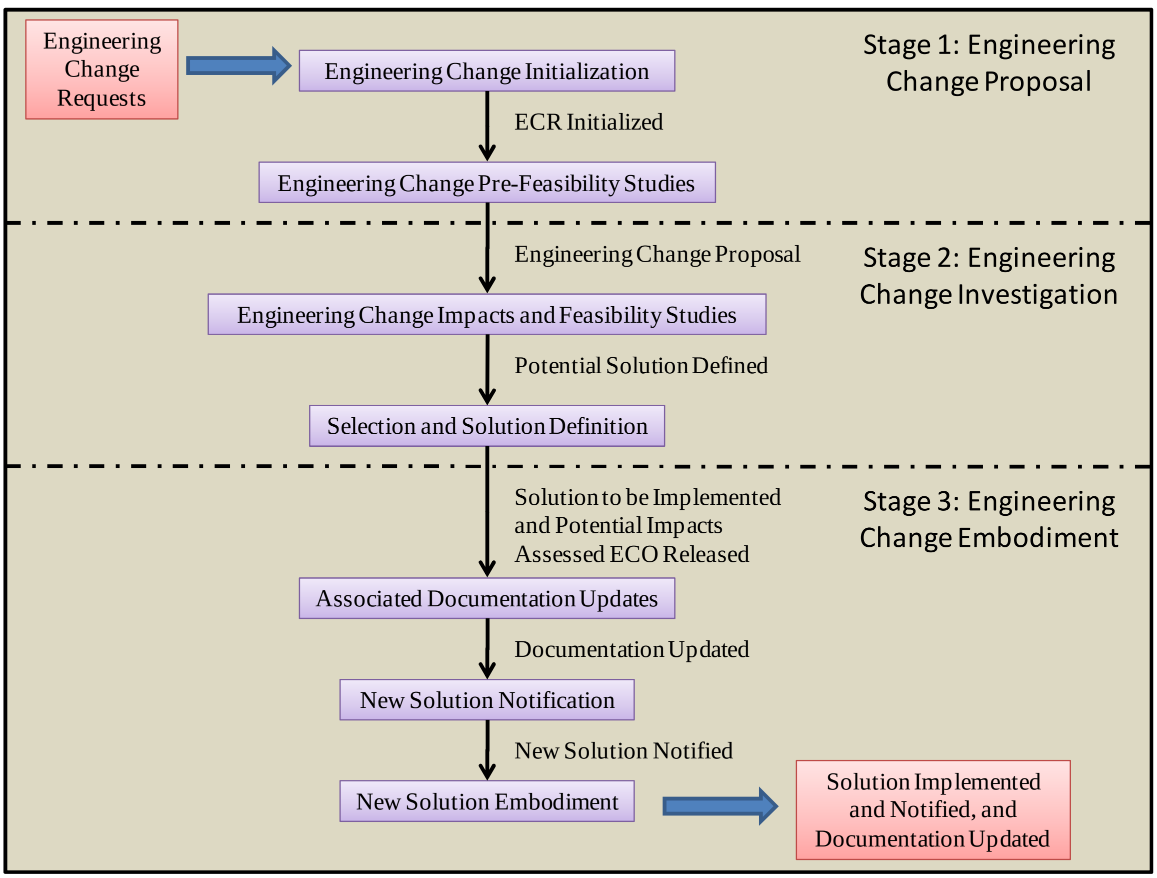


Figure 26: Collaborative Management of Engineering Changes [267]

An aspect of this framework that can be used to improve general change process is its proposed typology of interconnectivities to track potential change propagation, which is listed as follows [268]:

- **Association links –**progression of components' description throughout different stages of product lifecycle
- **Interface links –** closeness of two components in a product system such as their positioning, geometry and assembly process
- **Dimensioning links –** component property that affects definition of another such as how pipe design diameter is influenced by pump delivery rate
- **Organization links –** works shared by different business partners in product development process

To summarize, CM-EC framework is aimed to improve the efficiency of redesign process execution by creating a collaborative environment where change process can be executed with better data exchange and control. However, its application is tailored to conventional change strategies such as change front-loading and prevention that limits the inclusion of strategic planning for change implementation [267]. Its analysis measures also provide no insight on how the change process is best approached apart from evaluating its execution efficiency. While its suggested typology of interconnectivities covers aspects of product and process that can be affected by accommodation of engineering changes, no method or tool to improve and support the analysis is detailed out. Change impact analysis process within this framework is restricted by capabilities of existing PLM or PDM systems and experiences of product engineers, which lacks guidance for its decision-making process regarding change implementation [120, 199]. CM-EC also does not support simultaneous change propagation analysis [265]. On the whole, the main advantages and disadvantages of this method based on research objectives are listed in Table 5.

Table 5: Advantages and Disadvantages of CM-EC

Advantages	Disadvantages
• Improve overall efficiency of change management process execution through better product data exchanges • Assist prediction of change propagation paths through suggested typology of interconnectivities	• Lack emphasis on improving redesign planning process • Lack emphasis on improving and supporting change impact analysis • Do not support baseline assessment • Do not support simultaneous changes planning

2.3.2 Parameter-based Engineering Change Management

Rouibah and Caskey proposed a collaborative change management framework known as Parameter-based Engineering Change Management. Unlike CM-EC, this method is more focused on product change management instead of overall process efficiency. The main aspect of this framework is its product design parameter, which is defined as a particular circumstance of design variable in a given engineering situation [270]. It can be used to describe the dimensions of product components as well as their forces and movements. In reference to typology of interconnectivities in CM-EC, this parameter is a combination of interface and dimensioning links. Since most decisions in a collaborative design process are usually made at this parameter level, it becomes the best platform for cross-company communication and linking of processes, people and product items [270].

The outline of this method is depicted in Figure 27. In short, it starts with identification of required product changes that are mapped to their affected product parameters. Based on defined parameter interrelation or network information, other affected parameters through propagated change effects can be traced. These parameters are referred to their physical components and documentation, and all personnel and sub-contractors who are involved in the product changes implementation are identified based on this information. Detailed description on how to derive the parameter network is explained in [270].

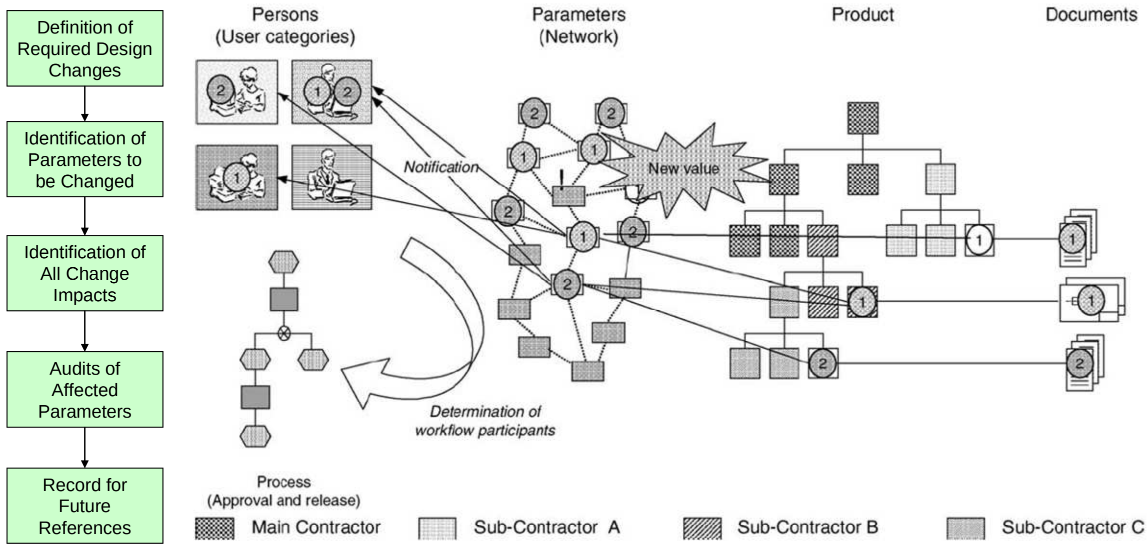


Figure 27: Parameter-based Engineering Change Management [270]

This collaborative, multi-company change management framework is developed based on concurrent engineering concept. It emphasizes on communication supports, collaborative involvement in change process, consensus in design decisions and management of change impacts [265, 270]. The latter criterion is the main driver behind parameter-based change propagation technique in this method. While it helps to distinguish possible propagation paths of the initial change effects, the overall process relies heavily on the experiences of decision makers and lacks strategic redesign decision-making support. Decision is made based on parameter values that depend on a compromise between various users, which is subject to biasness of their expertise or past experiences [265]. Furthermore, the inclusion of product attributes or parameters is totally dependent on user judgment and this creates modeling problems for complex product systems [265]. There has to be a proper scheme to balance the product model and the efficiency of its change process. Overall, the main advantages and disadvantages of this method based on research objectives are tabulated in Table 6.

Table 6: Advantages and Disadvantages of Parameter-based Change Management

Advantages	Disadvantages
• Improve overall efficiency of change management process execution through better product data exchanges • Assist prediction of change propagation paths through parameter-based tracking	• Lack emphasis on improving redesign planning process • Lack emphasis on improving and supporting change impact analysis • Do not support baseline assessment • Do not support simultaneous changes planning

2.3.3 Change Process Planning

Realizing that most available engineering change support methods and tools often ignore interconnections between a product and its development process, Eger et al. proposed an integrated design framework for planning product changes. They suggested that a proper planning method to guide product redesign process must have following criteria [120]:

- All design tasks involved in change implementation process must be considered during its planning
- Product designer must be aided in deriving the best change implementation plan, which is based on level of impacts for different alternative plans
- Resultant plan should provide estimates of incurred workload, cost and time delays that are associated with it, taking into account also possible indirect and propagated change effects

The representation of this planning framework is illustrated in Figure 28. It is comprised of four main stages: initial analysis, case analysis, solution space and task analysis. The first task is to construct a baseline product model. This involves identification of existing interconnections between baseline design parts, which are then assigned with an estimate of their change propagation risks. Next, driving requirements are translated into possible product modifications to satisfy them. Using information in the product model, the list of alternatives is screened out according to change propagation risks from directly affected parts. The decision to keep or discard implementation plan options depends on designer's experience but the provided mapping of interconnections should be able to assist them in identifying possible propagation paths that they might otherwise overlook. This is helpful when dealing with very complex architectures. Finally, implementation tasks outline for each change alternative plan is generated and the best redesign plan is chosen according to their associated risks.

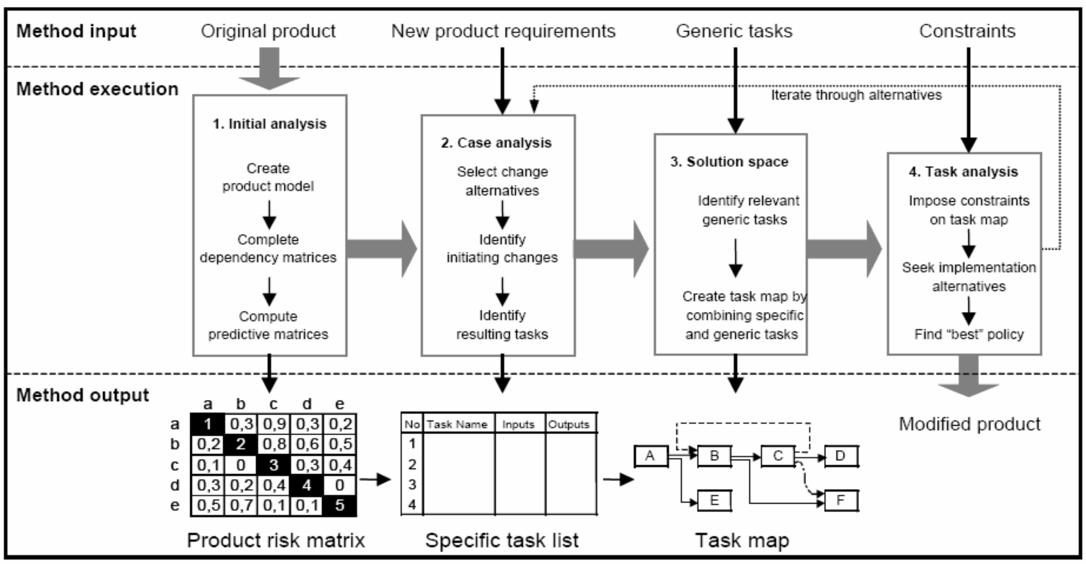


Figure 28: General Change Process Planning [120]

Though this process framework is well-structured to aid designers in planning for change implementation, methods and tools to be applied for each of its steps are still essentially under development [120]. Development of this framework is heavily tailored to Change Prediction Method (CPM) [273], which is discussed in next chapter. Due to its infancy state, some aspects of this framework need further refinements to improve its capability. For its case analysis in particular, a high reliance is placed on designer's experiences to accept or discard prospective change implementation plans. This is one of the identified problems for current change methods and tools. Even though it eases designer's task by identifying potential change effects, there is still a need for guidance in making change implementation decision because designers often have incomplete knowledge about their overall product system [80, 115]. Therefore, their decisions are biased towards what they know instead of the overall best. Provision of a proper reference can avoid inefficient or improper decisions for change alternative planning.

Furthermore, while the main idea behind the pursuit of this method recognizes the effects of engineering changes on product design, there seems to be no formal consideration on its performance impacts. This is another lacking aspect of current change methods and tools, which focus on process management issues but disregard the effects on redesigned product's capabilities [116]. In addition to the knowledge of which components that have to be modified and the processes to realize them, change effects on product performances are an important consideration as they dictate its ability to accomplish both its new and existing operational requirements [176]. The omission of a formal emphasis on this can be seen as the main deficiency of this method that needs to be resolved. On the whole, the main advantages and disadvantages of this method based on outlined research objectives are tabulated in Table 7.

Table 7: Advantages and Disadvantages of Change Planning Process

Advantages	Disadvantages
• Provide a structured workflow for redesign planning process • Provide a structured means to track change propagation and analyze its impacts on product development process	• Lack emphasis on strategic redesign decision-making • Lack emphasis on change impact analysis regarding product performances • Do not support baseline assessment • Do not support simultaneous changes planning

2.3.4 Reverse Engineering and Redesign Methodology

From main perspective of redesign practice, baseline product information offers a good basis to decide on potential path of its evolution, either it should be approached from its configuration, subsystem, component or parametric level [249]. This is useful for change decision-making procedure, particularly in planning and analyzing change impacts on a product and its process. A general design method for reverse engineering and product redesign is proposed by Otto and Wood [248], which is depicted in Figure 29.

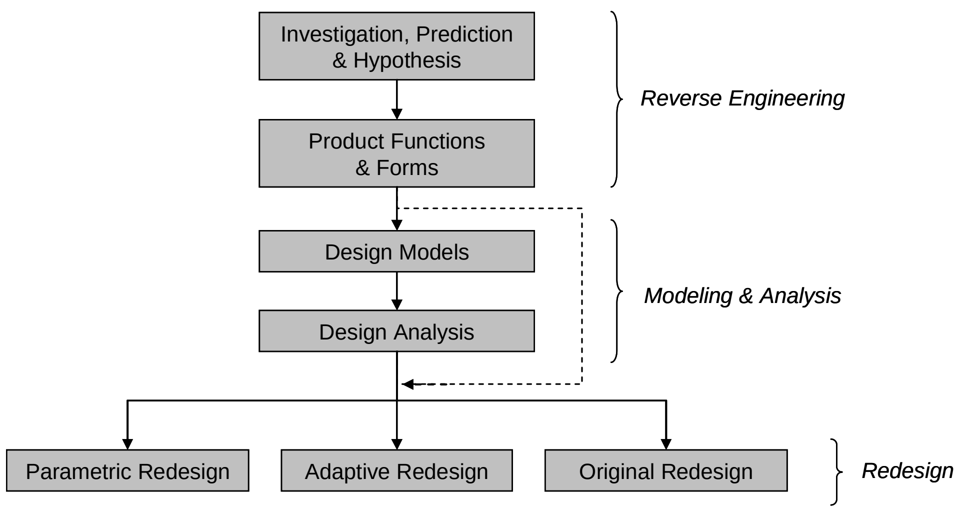


Figure 29: Reverse Engineering and Redesign Methodology [248]

This method highlights the fundamental steps to understand and represent a product prior to its redesign consideration [249]. It consists of three major phases: reverse engineering, modeling and analysis, and redesign. Although modeling approaches for product system often involve construction of mathematical-based or physic-based relationships, they are not always applicable or relevant for redesign process. This condition is indicated by the dashed line in Figure 29. In redesign planning for adaptive and original product variants, it requires qualitative knowledge about product composition to identify affected parts or subsystems. Mathematical-based relationships are typically used for parametric redesign, where existing product design is modified based on its optimization process.

This redesign framework offers a structured approach to guide designers in planning for their product variants, which is highly favored over ad-hoc approaches within educational and industry settings [68]. Application of reverse engineering process to extract necessary information about baseline product underlines the importance to have an accurate product system representation while making redesign decisions. However, it can be implied that execution of this method on complex products demands costly physical experiments and takes a long time to be completed. To obtain required information for creating baseline product model, this method requires the actual product to be disassembled and analyzed. In addition, baseline parametric model is developed through a manual "trial-and-error" process known as Subtract-and-Operate (SOP) [200, 249]. The high extent of manual processes in this method makes it unsuitable for complex product systems [247]. There is also no mention of a strategy to handle engineering changes during redesign process. This is a common paucity of available product redesign methodologies, which typically treat required modifications as a straight-forward design implementation problem.

All in all, the main advantages and disadvantages of this methodology based on outlined research objectives are tabulated in Table 8.

Table 8: Advantages and Disadvantages of Reverse Engineering & Redesign Method

Advantages	Disadvantages
• Provide basic workflow for redesign process • Support change impact analysis on product performances through manual experimentation	• Lack emphasis on strategic redesign planning • Lack emphasis on change propagation analysis • Do not support baseline assessment • Do not support simultaneous changes planning

2.3.5 "Anchoring and Adjustment" Redesign Process

Dixon and Colton suggested that many product redesign cases have been executed in an ad-hoc manner because no universal guidance is available to designers [104]. Based on their "anchoring and adjustment" process model, they proposed a redesign management strategy that was aimed to understand and manage the manner designers approach their product redesign problems [68]. In general, it is developed to capture the common human reasoning and judgment heuristics that dictates the way existing product is redesigned for new requirements. The "anchoring and adjustment" heuristic relates to the approximation of redesign solution based on closely similar problem that has already been solved in the past [104]. The illustration of this redesign strategy is shown in Figure 30.

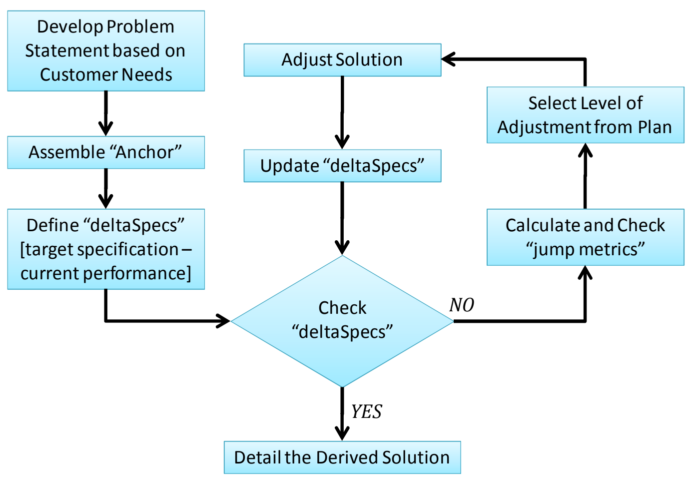


Figure 30: "Anchoring and Adjustment" Redesign Process [104]

In short, the process starts with identification of design change needs. Next, an "anchor" is selected to approximate the redesign solution based on its proximity to the real problem in hand. Alternatively said, the "anchor" is an already resolved design problem in the past that has similar characteristics to the current problem. An evaluation metric, "deltaSpecs" is defined to measure relative improvements made on the estimated solution towards the perceived actual solution. Adjustment to the solution is made iteratively and the value of "deltaSpecs" is re-calculated. Another metric, "jump metric" is defined to determine if a big “jump” in change or adjustment level is necessary when no significant improvement to the value of “deltaSpecs” is recorded. This process is continued until the “deltaSpecs” value is 0 or falls within a specified tolerance range, or when the value of “jump metric” exceeds the prescribed stopping criterion.

The selection of appropriate “anchor” mimics the emphasis on choice of baseline design. While this method provides a clear workflow for product redesign approach, designers still have to manually generate the adjustment plans. Therefore, the success or failure of the redesign development highly depends on their capability to create appropriate change plans based on their experiences [68]. This situation does not improve the pressure that designers currently have to endure in planning for their product redesign or aid them from making errors in their decision-making. Furthermore, application of this method seems to be designated for one modification per run by focusing on one target performance metric. As argued before, there are often multiple initial changes that need to be simultaneously considered in real product development cases because their impacts are interrelated.

In summary, the advantages and disadvantages of this redesign method based on research objectives are tabulated in Table 9.

Table 9: Advantages and Disadvantages of “Anchoring & Adjustment” Redesign

Advantages	Disadvantages
• Provide a structured redesign process based on target specification • Support impact analysis on a pre-determined target metric	• Lack emphasis on strategic change planning • Do not support change propagation analysis • Lack detailed emphasis on change impact analysis • Do not support simultaneous changes planning • Do not support baseline assessment

2.3.6 "Design for Assembly"-based Product Redesign Approach (DBPRA)

Design for assembly (DFA) methodologies are well-recognized in product manufacturing industries, which are developed to bring forward issues regarding assembly operations to early product design stages [150]. Despite proven benefits of DFA methods in increasing manufacturer's competitiveness by reducing part-count, simplifying product structure and improving reliability of their new original design development; little attention has been made to apply its scheme to product redesign case [163]. Realizing the potential from this overlooked viewpoint, Hsu and Lin proposed a product redesign method that essentially combines functional analysis and design for assembly (DFA) assessment. The method is called design for assembly-based product redesign approach (DBPRA), which is shown in Figure 31.

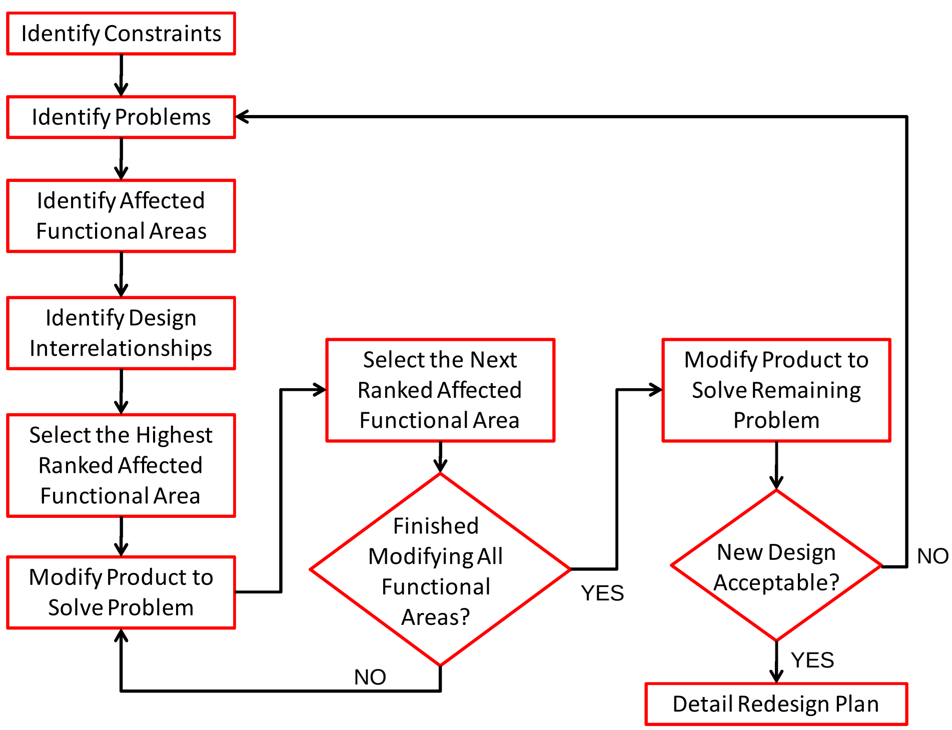


Figure 31: Redesign Procedure in DBPRA [163]

The process starts when market requirements impose a modification on existing product design. Based on that, potential assembly problems that could result from the change are identified. Next, necessary constraints and redesign targets are outlined to govern design solutions. The existing product is analyzed through functional analysis and all functional areas that are affected by redesign process are identified. After that, the product design is further examined to extract all physical relationships that exist between its parts such as its underlying interface networks. Once this is determined, the redesign process is ready to be executed. Functional area that is affected the most is selected first and necessary product design changes to resolve it are derived. Next, the second-ranked functional area is considered and resolved, and this cycle is continued until all affected functional areas have been resolved. Remaining redesign problems after that, which are not related to any product functional areas, are later considered and solved. Finally, the modified product is assessed to see whether all problems have been resolved. If not, the process is reiterated until there is no redesign problem left.

This methodology introduces a structured workflow on how a redesign problem could be approached. Its application assists product designers in identifying promising adaptation plans for “local changes” (component parametric changes) and “global changes” (system level functions) [163]. Another aspect that is highlighted by this method is the ranking of initial changes to be executed. Since different requirements can affect similar components in conflicting manner, the ranking will determine which of them has a priority over the others. Nonetheless, its high dependence on DFA scheme constricts the identified change problems to only assembly-related issues [68]. In this method, change problems have to be translated into their potential assembly-related issue, which reduces the transparency of the problem and increases the potential to overlook interrelationship between initiating change problems. Furthermore, the core assumption of functional independence between product’s functional areas can overlook many interrelated change effects that should have been simultaneously considered during product redesign planning.

All in all, the advantages and disadvantages of this redesign method based on research objectives are tabulated in Table 10.

Table 10: Advantages and Disadvantages of DBPRA

Advantages	Disadvantages
• Provide a structured workflow for redesign process • Manual support of change impact determination through functional analysis	• Lack emphasis on strategic redesign planning • Lack emphasis on change propagation or impact analysis • Do not support simultaneous changes planning • Do not support baseline assessment

2.3.7 Comparison of Identified Methods to Research Objectives

From above discussions, available product redesign and change management frameworks do address parts of the outlined research objectives. While none of them independently provides a detailed solution for identified research areas in this study, their good process characteristics can be combined to form a better platform for the new proposed method. It can be observed that the main reason for this condition is the inherent separation of their application, whereby none of the identified product redesign methods considers change management in their procedure and vice versa. This is in spite of the fact that there exists a close relationship between these two areas of product development, which solidifies the relevance of this thesis study to current product industry practices.

The advantages and disadvantages of all identified methods are summed up in a Strength, Weakness, Opportunity and Threat (SWOT) plot depicted in Figure 32. In short, SWOT is an analytical method that is used to formulate new strategy by qualitatively evaluates the competitiveness of current one [195]. Its appreciation of strengths and weaknesses, as well as external market opportunities and threats, is highly beneficial to strategically plan for preferred performance targets in relative to the competition [162]. In this assessment, identified product redesign and change management process frameworks are collectively reviewed and interpretation of their combined SWOT plot is slightly modified as follows. First quadrant shows their combined strengths that offer market opportunities to product manufacturers. On the other hand, their weaknesses that can provide market opportunities if strengthened are listed in second quadrant. Finally, desired process characteristics from outlined research objectives that are lacking in all identified frameworks are highlighted in joint third-and-fourth quadrant. These missing criteria have been argued to potentially threaten manufacturers' market competitiveness with regards to the effectiveness of their redesign process.

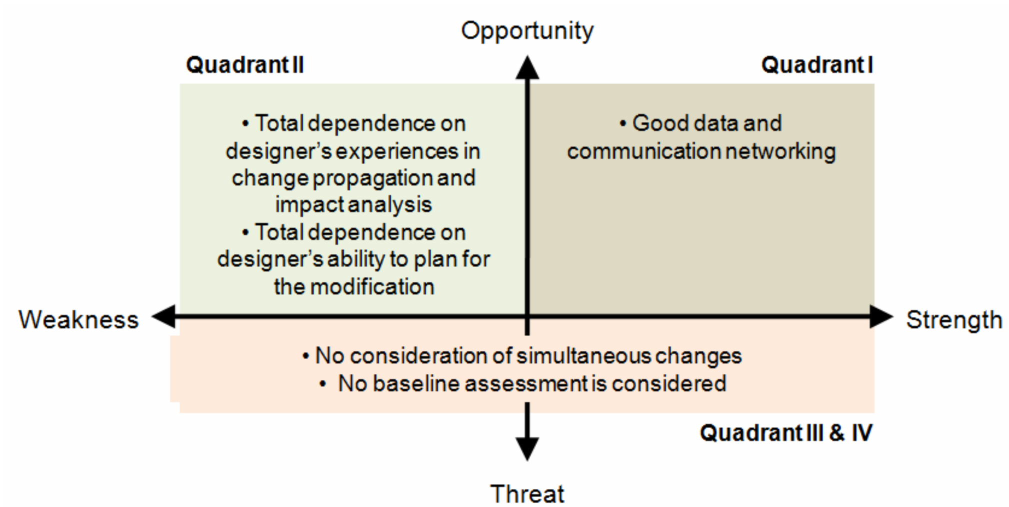


Figure 32: SWOT Plot for Identified Engineering Change Frameworks

Product data management process has progressively improved over the last few years and is the sole identified strength from this review. This is in line with previous findings that available change support tools have been mostly focused on smoothing data sharing and networking in redesign process. This strength of current methods can be readily exploited by the proposed method, as highlighted by quadrant I. On the other hand, criteria listed in quadrants II and III & IV highlight shortcomings of identified frameworks with respect to research objectives. They can be classified into four main areas of concentration for the proposed method: baseline assessment, change propagation modeling, change impact analysis and change implementation planning. Individual assessment and comparison of identified process frameworks with respect to these four areas are tabulated in Table 11. This qualitative assessment is made based on their reference literatures.

Table 11: Qualitative Comparison of Identified Process Frameworks

Areas of Concentration	Brief Description	CM-EC	Parameter-based ECM	Change Process Planning	Reverse Engineering & Redesign	"Anchoring and Adjustment" Redesign	DBPRA
Baseline Assessment	Establish measures of a good baseline design with regards to required modification	★ Do Not Support	★ Do Not Support	★ Do Not Support	★ Do Not Support	★ Do Not Support	★ Do Not Support
Change Propagation Modeling	Model product system in a way that potential change effects propagation can be easily tracked	★ Fair	★ Excellent	★ Excellent (best)	★ Do Not Support	★ Do Not Support	★ Fair
Change Impact Analysis	Assess total impact of executed engineering change	★ Fair	★ Do Not Support	★ Good (best)	★ Fair	★ Fair	★ Fair
Change Implementation Planning	Establish criteria of a good change implementation plan to aid decision-making process	★ Do Not Support	★ Do Not Support	★ Good (best)	★ Do Not Support	★ Fair	★ Fair

LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent ▭ Best per criterion

All these frameworks have a well-structured process flow that can be used as a reference platform for the proposed redesign methodology but none of them matches the intended capabilities in accordance to specified research objectives. The closest amongst them is change process planning method. While it supports change implementation planning; its scope is focused on tasks planning instead of deciding strategically how to accommodate changes from the viewpoint of product and its process. It also does not address baseline redesign suitability, which is crucial to justify the decision to redesign a product against developing a new original design. In fact, none of identified change frameworks provides a formal support to assess baseline suitability. A few baseline candidates are available in many cases of product derivative development and their choice will influence the success of the redesign development. A bad baseline choice will complicate the redesign process; contributing to high costs and long development time.

Since the proposed aircraft redesign method is expected to overcome these shortcomings, several research questions have been formulated for their clarification and they are listed as follow.

1. How to assess whether the redesign risks associated with selected baseline aircraft are manageable?
   I. What are characteristics of a good baseline for aircraft redesign approach?
   II. How these characteristics affect the change process?

2. How to efficiently capture potential change effects propagation within an aircraft system?
   I. How engineering change effects propagate from one architecture locality to another?
   II. What are control parameters of change propagation?
   III. How to properly model aircraft system to predict change propagation?
3. How to assess impact of engineering changes on aircraft and its development process?
   I. What are characteristics of aircraft and its development process that can be affected by engineering changes?
   II. How to sufficiently measure change impacts on these characteristics?
   III. How to manage overall aircraft redesign risks?

4. How to competitively plan for required engineering change implementation into existing aircraft system?
    I. What are important criteria for a good change implementation plan?
    II. What are available control parameters in change planning?
    III. How to generate implementation plan for required changes?
    IV. How to select the best change implementation plan among possible alternatives?

These questions guide literature review in next chapter and become the foundation for the proposed redesign method, which is called "Strategic Planning of Engineering Changes" (SPEC).

2.3.8 Strategic Planning of Engineering Changes (SPEC) Framework

With respect to observation made in aircraft derivative development process and research questions that emerge in previous section, their association with the steps of the proposed method is shown in Figure 33.

Sequence of steps for the proposed SPEC method is illustrated in Figure 34. In brief, the main inputs for the methodology come from requirements analysis, PDM or PLM system and preliminary candidate(s) for the baseline design. Having all these inputs, the first step is to model considered baseline candidates in such a way that change effects propagation can be efficiently predicted. Next, the model is applied to assess baseline suitability with regards to required modifications that have been established from requirements analysis, which is not part of this method. This baseline assessment stage could also be a selection step if multiple baseline candidates are preliminarily considered. If the baseline is valued to be flexible enough for redesign development, possible change implementation plans are generated. These plans are passed on to change impact analysis step, where the effects of their proposed modification on both product and its process are estimated. Based on this analysis results, the change proposal options are ranked with respect to some defined evaluation criteria. This method concludes with selection of the best engineering change implementation plan, which becomes an input into formal change management process in the company.

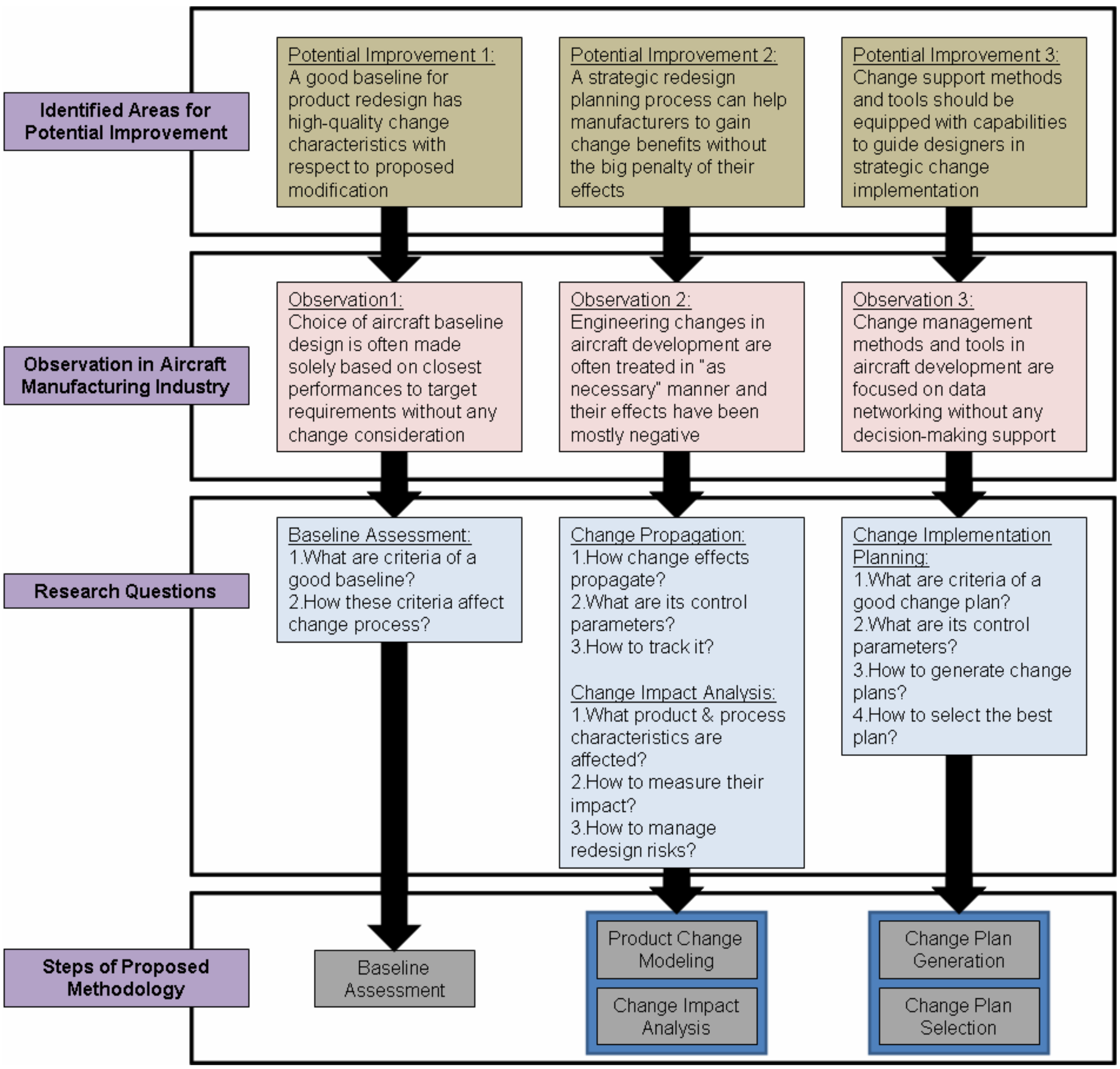


Figure 33: Relationships of Observations, Research Questions and Proposed Method

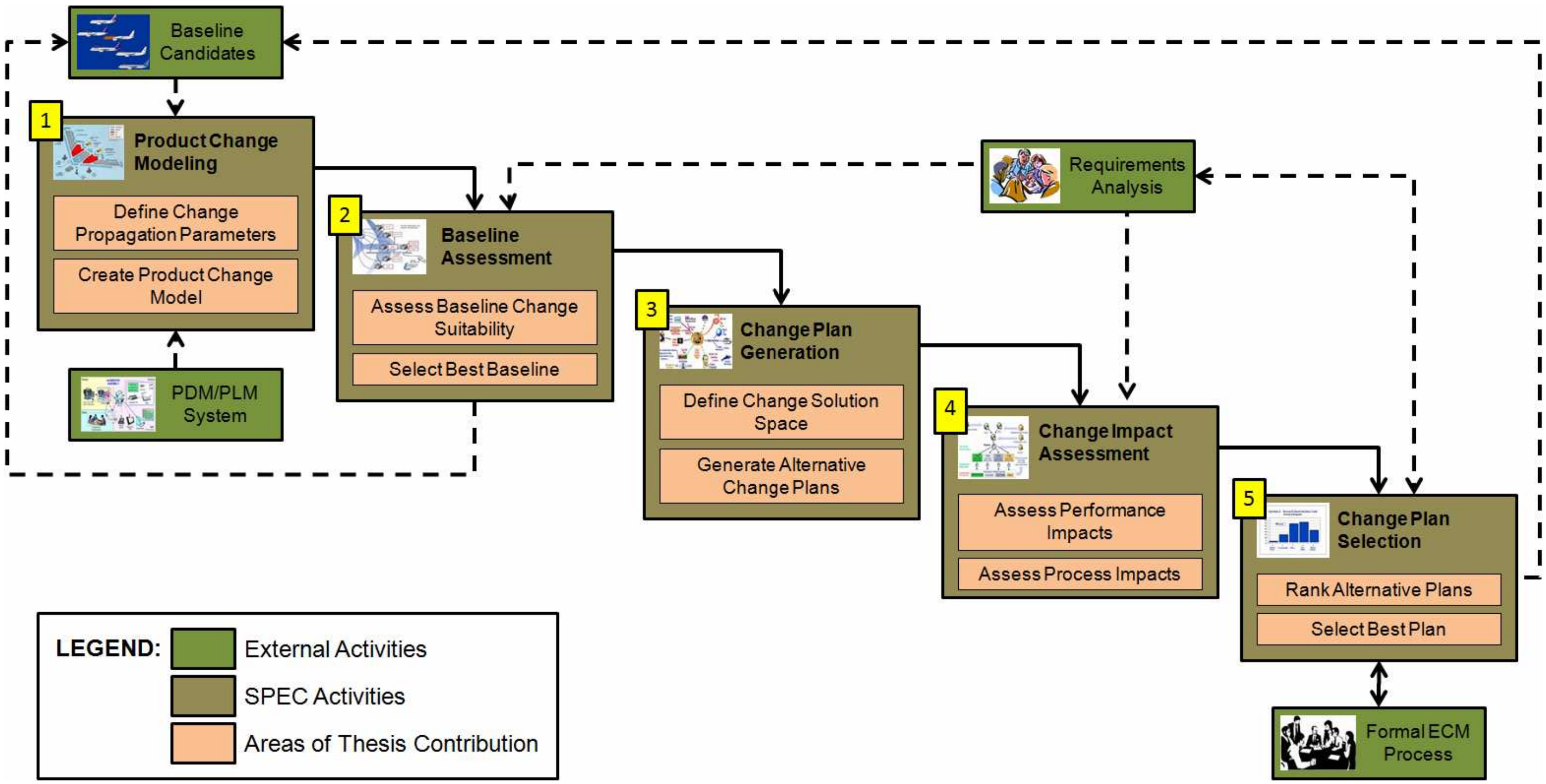


Figure 34: Proposed Framework for SPEC Method

The process framework in Figure 34 is not yet complete and several high-level research questions regarding its overall workflow need to be addressed by literature review in next chapter. These questions are listed as follow:

1. What are detailed inputs and outputs for each step in the framework?
2. What are specific techniques and tools required to accomplish each step?
3. Is any iteration process necessary within the framework?

2.4 Chapter Summary

It has been discussed throughout this chapter the big role that derivative development has in aircraft manufacturing industry. This redesign strategy is frequently applied by aircraft manufacturers to maintain their competitiveness amid increased market competition and to satisfy emerging trend of customized demands from airlines. Complexity of aircraft design and collaborative nature of its development translate into a complicated redesign process, which makes it an exemplary case to demonstrate the proposed SPEC method.

Without proper assistance from available engineering change methods and tools, aircraft engineers have to manually plan derivative redesign based on their previous experiences. They tend to follow notions from available design methods that have been developed for original development [104] and this often leads to overlooked change effects that have to be unexpectedly handled during late phases of the development process. For high risk and high cost products like aircraft, these late changes are detrimental to their manufacturers' competitiveness and market image. Potential benefits of a structured change management in product redesign process have been preliminarily demonstrated by several concurrent engineering methods and tools. Dassault Aviation reported a reduction of design cost and production time by almost 50% for Falcon 7x aircraft development in comparison to their normal rate by supporting the process with a better collaborative workspace environment

[50]. It has been argued that more advantages can be gained by manufacturers if elements of strategic redesign planning are also included in the capabilities of change methods and tools, on top of their current focus to increase the efficiency of process execution.

Several redesign and change management process frameworks that are currently available have been preliminarily assessed to identify potential improvements based on observation in these first two chapters. Although none of them possesses all desired capabilities, their assessment helps to recognize current gaps that need to be focused in the formulation of the proposed method. One highlight from this review is the traditional separation between methods for product redesign and engineering change management, even though they are closely related in securing product market success. It is believed their combination into a single methodology can greatly benefit aircraft manufacturers in their redesign process. Based on the knowledge gained so far, initial formulation of steps for the proposed SPEC method has been constructed. The outlined research questions are used to guide literature review study presented in next chapter.

CHAPTER 3

LITERATURE REVIEW

"It is neither desirable nor realistic to focus one's effort on simply eliminating the engineering changes."

- Clark and Fujimoto (1991)

In the big picture, the proposed SPEC methodology fundamentally combines the aspects of product redesign, change management and strategic change implementation planning processes. A case is made in this chapter that even though none of the existing works deal directly with the focused problem for this thesis study, there are some areas that they can contribute in the formulation of the proposed method. The two main goals of this chapter are to identify the positive and negative aspects of available methods and tools, and to assess their relative performance gaps to the specified research objectives in Chapter 1. This provides the basis and further justification to the research hypotheses to be defined in next chapter.

This literature review is tailored to four main research areas that have been established in preceding chapter: baseline assessment, change propagation modeling, change impact analysis and change implementation planning. Some of the available state-of-the-art tools that can address the recognized problems in these areas of study and how their knowledge can improve the current change management frameworks are identified. The shortlist of identified methods and tools is presented in Table 12, and they are discussed in details within this chapter. Although there are other identified methods and tools in this literature study, only the major ones that contribute towards the formulation of the proposed SPEC method are included and discussed here.

Table 12: Identified Tools and Methods in Research Areas

Research Areas	Identified Tools and Methods				
	1	2	3	4	5
Baseline Assessment	Quantitative System Evolvability	System Adaptability Factor (SAF)	Method for Assessing the Adaptability of Product (MAAP)		
Change Propagation Modeling	Functional Change Modeling	Component-Function Propagation Model	Component Linkage Model	Change Favorable Representation (C-FAR)	Product Dependency Model
Change Impact Analysis	Change Propagation Analysis	Progressive Probabilities of Changes	Response Surface Method (RSM) in Change Impact Assessment		
Change Implementation Planning	Redesign-IT	KRITIK	Change Prediction Method (CPM)		

3.1 Baseline Assessment Methods

Electronic Industries Alliance's EIA649 Standard describes a baseline design as an "*agreed-to-description of the product attributes at a point in time that provides a known configuration to which changes are being addressed*" [297]. This definition supports the notion that the state of product architecture will influence how engineering changes can be implemented into it [332]. A proper baseline selection is imperative because the benchmarking of redesigned product is made with respect to its predecessor [82]. An improper baseline might mislead the actual benefits and risks of the redesign process.

In general engineering design, the measure of product's ability to be adapted towards the changes in its environment, requirements and/or technological advancements is often referred to as "*evolvability*" [271]. It corresponds to the required degree of product design changeability to satisfy the new requirements without compromising the integrity of its current architecture [158, 272] and with a more cost-effective development process than building a new product for similar purpose [74]. The accommodation of changes is dictated by the state of product architecture and based on the driving requirements; different baseline systems might require different levels of modification. This highlights the profound implication of product design architecture on manufacturer's ability to execute the redesign development process [326]. In view of that, this section is focused on addressing the following research questions:

1) What are characteristics of a good baseline aircraft for the redesign approach?
2) How will these characteristics affect the change process?

In this literature review, no known formal method is found to be directly focused on the assessment of baseline suitability for product redesign, particularly from the viewpoint of its architecture. While there are several standard definitions that have been proposed to guide the evaluation process; having a structured, quantitative means to select the product baseline is more beneficial [311]. Rowe et al. proposed evaluation metrics for software system's capability to accommodate modification in [272] and it is believed that they can be extended to hardware products. A generalized description of these metrics from the viewpoint of engineering product architecture is given as follows:

- **Adaptability**: ability to modify or add modules without affecting other existing modules
- **Changeability**: ease of making changes to the product or system
- **Flexibility**: ease of rearranging or modifying the interrelationships between different modules to suit the new requirements
- **Extensibility**: ability of the architecture to support new functions and changes
- **Enhanceability**: ease of incorporating new functionalities into the existing architecture

In separate study, Fricke and Schulz expanded the changeability definition of physical product design into its basic principles of simplicity, independence and modularity [138]. Simplicity or ideality of a product architecture design is measured by its number of interfaces, secondary functions and types of resources required, whereby the simplest one corresponds to the minimum values for each of them [35]. Conversely, the highest level of architecture independence is present in the products with minimum affected design parameters during the change implementation whereas the highest modularity measure is linked to the minimum number of couplings between different product subsystems [286]. It can be inferred from these definitions that the preferred redesign process affects the smallest number of parts or subsystems, requires the least amount of new subsystems or interrelationships and has the lowest development risks and costs. While these criteria are clearly recognized, no structured measurement technique that properly relates them to the product architecture is found.

Based on this realization, as well as the presented arguments in previous two chapters, several criteria are outlined to compare the advantages and disadvantages of the identified methods for baseline assessment. They are listed as follows:

(i) Provide a structured baseline evaluation scheme
   a. Clearly define evaluation metrics to assess the suitability of product with regards to the required changes
   b. Assist the assignment of values for these metrics

(ii) Suitable for considered scope of redesign process
   a. Provide evaluation metrics that capture the essences of product redesign process during its conceptual and preliminary stages
   b. Include consideration of engineering change process

(iii) Scalable to specific engineering change evaluation
   a. Allow the evaluation focus on specific engineering change situation

3.1.1 Quantitative System Evolvability

According to Christian and Olds, all engineering systems can accommodate their required changes either statically or dynamically [75]. In separate works by Saleh et al., these two categories of product's evolvability characteristics are designated as robust and flexible, respectively [277]. These system characteristics can be further decomposed as shown in Figure 35, which is closely tailored to the taxonomy of change that have been proposed by Rowe et al. [272]. These four classes of system evolvability correspond to different ways that the new requirements can be satisfied by the baseline design, which are briefly described in Table 13.

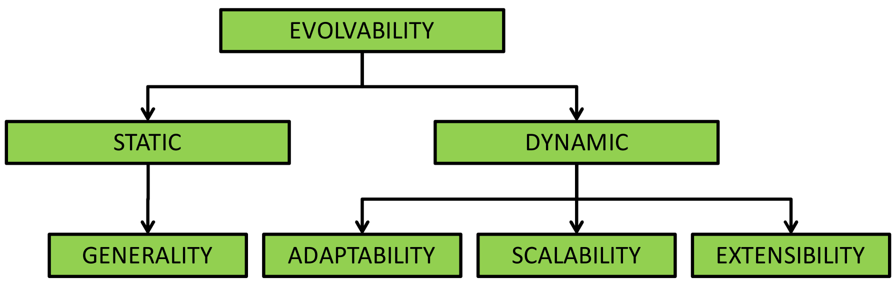


Figure 35: Functional Breakdown of System Evolvability [75]

Table 13: Classes of System Evolvability [74, 75]

Evolvability Class	**Description**
Generality	The capacity of a system to accommodate a change in requirements without altering the existing architectural design or implementation strategy
Adaptability	The capacity of a system to accommodate a change in requirements through rearranging existing system components within the current architecture without changing other components or their integration solution
Scalability	The capacity of a system to accommodate a change in requirements by increasing the size of architectural components to accommodate increased loads
Extensibility	The capacity of a system to accommodate a change in requirements through adding new components or through a major change in the architecture or implementation strategy

Based on this definition, product evolvability is an aggregate quantity that combines the measures of how well it can accommodate the required modification in accordance to its generality, adaptability, scalability, and extensibility capabilities. For this assessment scheme, the system is measured by its difficulty level to be modified to achieve the target requirements. The quantitative measure is tailored to a qualitative rating scale known as Difficulty Scale of Evolvability Analysis (DSEA), which is presented in Table 14.

Table 14: Difficulty Scale for Evolvability Analysis [75]

Rating	Explanation
1	Easy – Requires little effort to evolve. Some new technologies might be implemented but the functionality of most system components remains unchanged. The complexity level of the system also remains almost the same.
3	Moderate – Requires moderate effort to evolve. Some new technologies might be implemented and the functionality of some system components is changed. The complexity level of the system increases a little.
9	Difficult – Requires large effort to evolve. Many new technologies are required and the functionality of most system components is changed. The complexity level of the system substantially increases.
27	Very Difficult – Requires very large effort to evolve. Many new technologies are required and the functionality of most system components is significantly changed. The complexity level of the system greatly increases.

Before the individual ratings are combined into a single evolvability metric, they are normalized using standard scoring functions. The proposed scoring function is introduced by Wymore [346] and it comprises 12 basic Wymorian shapes of the family function. The full description of these functions is available in [100] and the ones applied in this measurement scheme are SSF1 and SSF7, which refer to “the larger the better” and “the smaller the better” cases, respectively. These functions enable a combination or comparison of metrics that lack a common basis [100]. For instance, in a case of “smaller the better”, a saving of 20 kg can be of less significance to product designers when their total product weight is already more than 100 kg but the same amount of weight savings is a significant improvement when the total weight is below 100 kg. In other words, these Wymorian functions allow the definition of a threshold where data difference matters more than when they are located outside the range. This differs from most measurement techniques that normalize data to maximum or minimum value and ignore the underlying weights for each data value against each other. The SSF1 and SSF7 scoring functions are depicted in Figure 36 and their mathematical representations follow.

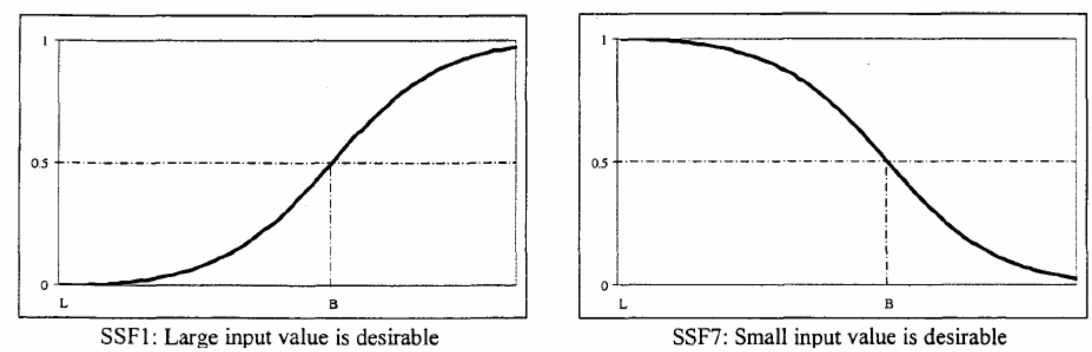


Figure 36: Plots of Wymorian Standard Scoring Functions SSF1 and SSF7 [74]

$$SSF1(L,B,S,D) \quad Score = \frac{1}{1+\left(\left(B-L\right)/\left(v-L\right)\right)^{2S\left(B+v-2L\right)}} \qquad \text{Equation 1 [74]}$$

$$SSF7(L,B,S,D) \quad Score = 1-\frac{1}{1+\left(\left(B-L\right)/\left(v-L\right)\right)^{2S\left(B+v-2L\right)}} \qquad \text{Equation 2 [74]}$$

where: $v =$ input value for the metric

$Score =$ output of the scoring function

$L =$ lower threshold of the input value

$B =$ baseline value for the metric [by definition, this is always defined as a score of 0.5]

$S =$ slope of tangent to the scoring function at the baseline value, which represents the maximum incremental change in the user quantitative judgment

$D =$ domain of definition of the scoring function

Finally, the overall system evolvability measure is defined as follows:

$$Total\ evolvability,\ f = \sum_{i=1}^{n} w_i x_i \qquad \text{Equation 3 [74]}$$

$n =$ total number of metrics to be added, $w_i =$ normalized weight for metric i
$x_i =$ score of metric i

For generality measure, or also known as "do-nothing" alternative, a score of 1 is given if the evolved requirements are within the capability of the existing product design. Else, a score of 0 is given instead. On the other hand, the scalability measure is calculated using SSF7 function while both adaptability and extensibility measures with SSF1 function.

To summarize, it can be observed that the method stays close to the standard definition of system evolvability and introduces good qualitative metrics based on existing product design. However, it should be noted that the most evolvable design is not always the best baseline for the redesign practice as other important factors such as modification costs and development risks should also be taken into consideration [75]. Apparently, they are not considered in this scheme. On the whole, the advantages and disadvantages of this method are summarized in Table 15 and its qualitative comparison to the characteristics of baseline assessment specified for the proposed SPEC method is given in Table 16.

Table 15: Advantages and Disadvantages of the Quantitative System Evolvability

Advantages	**Disadvantages**
• Provide a clear definition of potential baseline assessment metrics • Provide a structured evaluation scheme	• No assistance on valuation of the evaluation metrics • Not directly applicable for specific engineering change assessment

Table 16: Qualitative Comparison of Quantitative System Evolvability

Required SPEC Characteristics	Quantitative System Evolvability
Provide a structured baseline evaluation scheme	★
Suitable for considered scope of redesign process	★
Scalable to specific engineering change evaluation	★
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.1.2 System Adaptability Factor (SAF)

Engel and Browning proposed an extension to the Standard ISO/IEC 9126-1 for software engineering qualities to be the essential measures for evaluating product architecture flexibility [125]. Although these standard quality assessment measures have been tailored towards software systems, they can also pertain to hardware products due to their generic definitions [125, 136]. The six categories of these factors are listed in Table 17.

Table 17: ISO/IEC 9126-1 Characteristics and Sub-characteristics [136]

Characteristics	Sub-Characteristics
Functionality	Suitability, Accuracy, Interoperability, Security, Functionality Compliance
Reliability	Maturity, Fault Tolerance, Recoverability, Reliability Compliance
Usability	Understandability, Learnability, Operability, Attractiveness, Usability Compliance
Efficiency	Time Behavior, Resource Utilization, Efficiency Compliance
Maintainability	Analyzability, Changeability, Stability Testability, Maintainability Compliance
Portability	Adaptability, Installability, Coexistence, Replaceability, Portability Compliance

Accordingly, the quantification of measure for product design flexibility, which is known as System Adaptability Factor (SAF), is further described in Table 18. Derivation of the metric measurement can be referenced to its sub-characteristics in Table 17. None of the standard sub-characteristics is compulsory and their choices depend on engineering system under interest. A weighting factor for each metric is allocated within a qualitative scale of [0,1], which is assigned to indicate their significance level in affecting the system adaptability criteria [125]. Mathematically, the weights have to satisfy following conditions:

$$\sum_{i=\{F,R,U,E,M,P\}} W_i = 1 \qquad \text{Equation 4 [125]}$$

Table 18: Adaptability Metrics Description [125]

Metric	Variable	Weight	Description
Functionality	F	W_F	Capability of the system to provide functions that meet the requirements when used under specified working environment
Reliability	R	W_R	Capability of the system to maintain its level of performance when used under specified working environment
Usability	U	W_U	Capability of the system to be understood, learned, used and liked by the user when applied under specified working environment
Efficiency	E	W_E	Capability of the system to provide the required performance relative to the amount of resources used
Maintainability	M	W_M	Capability of the system to be modified, which may include corrections, improvements and adaptation to changes in environment, requirements and functional specifications
Portability	P	W_P	Capability of the system to be transferred from one environment to another

Finally, model for the overall SAF measurement is defined as the weighted average of the six adaptability metrics:

$$SAF = W_F F + W_R R + W_U U + W_E E + W_M M + W_P P \qquad \text{Equation 5 [125]}$$

The main emphasis of this assessment is for a new product design development. While these SAF metrics can be influential for product success, some of them are not effective in evaluating baseline suitability for the redesign process such as portability criterion. From their description in Table 18, the only metric that is directly related to redesign process is maintainability criterion. However, no guideline for its evaluation with regards to existing product architecture is provided in this method.

On the whole, the advantages and disadvantages of this method are summarized in Table 19 and its qualitative comparison to the desired characteristics of baseline assessment for the proposed SPEC methodology is given in Table 20.

Table 19: Advantages and Disadvantages of SAF

Advantages	Disadvantages
• Provide a clear definition of potential baseline assessment metrics • Provide a structured evaluation scheme	• No assistance on valuation of the evaluation metrics • Not directly applicable for specific engineering change assessment

Table 20: Qualitative Comparison of SAF

Required SPEC Characteristics	SAF
Provide a structured baseline evaluation scheme	★ (Fair)
Suitable for considered scope of redesign process	★ (Fair)
Scalable to specific engineering change evaluation	★ (Fair)
LEGEND: Do Not Support, Fair, Good, Excellent	

3.1.3 Methodology for Assessing the Adaptability of Products (MAAP)

According to Willems et al., the main pre-requisite for reusing or redesigning an existing product is the feasibility of its adaptation process, which is influenced by its design [339]. In other words, the extent on how a product system can be redesigned or reused depends on its current architectural build-up [340]. Acknowledging this fact, Methodology for

Assessing the Adaptability of Products (MAAP) is proposed to evaluate the suitability of product design for remanufacturing, repair, maintenance and upgrading/downgrading, which are the processes involved in typical product adaptation procedure [339]. Under the scope of this MAAP method, product adaptation is viewed as an extension of usage for the existing products beyond their designated operational life [288, 340]. Therefore, it measures the product suitability to be modified for a different function than the one it was initially designed for.

Based upon the common task demands for remanufacturing, repair, maintenance and upgrading/downgrading processes, three additional categories of product parameters are included into the adaptation metrics [19, 340]. They correspond to the design architecture composition of the product, which are generalized as parts, connectors and spatial metrics [340]. The adaptation metric is thus comprised of seven sub-metrics as shown in Figure 37, which can be further decomposed into their lower level criteria to qualitatively guide their value assignment. The calculation for overall product adaptation measure in this MAAP method is given as follows:

$$\mu Adaptation = \frac{1}{GF + 0.5\left[\frac{W_{reman.}}{\mu_{reman.}} + \frac{W_{main.}}{\mu_{main.}} + \frac{W_{repair}}{\mu_{repair}} + \frac{W_{up/dowm}}{\mu_{up/down}}\right]} \quad \text{Equation 6 [340]}$$

$$GF = \left(\frac{W_{spatial}}{\mu_{spatial}} + \frac{W_{connectors}}{\mu_{connectors}} + \frac{W_{parts}}{\mu_{parts}}\right)$$

$$W_{reman} + W_{main.} + W_{repair} + W_{up/down} = W_{spatial} + W_{connectors} + W_{parts} = 1$$

where W_i = weighting of metric i and μ_i = valuation of metric i

The valuation for each adaptation metric and their weighting is further discussed.

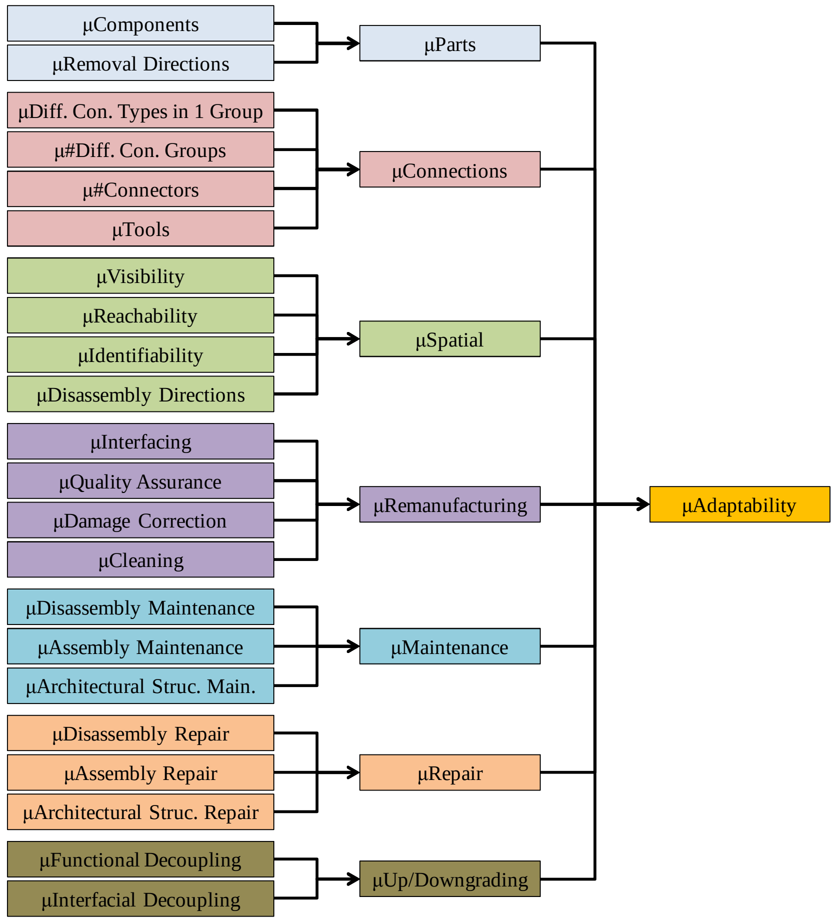


Figure 37: Structure of the Adaptation Metric [339]

Despite the subjectivities surrounding the metric values [147], the general guide for their valuation has been suggested based on Design for Assembly (DFA) methods [52, 340]. For parts, connectors and spatial metrics, they are specified by the ratio of their theoretical minimum to their actual present value. For example, from the viewpoint of its parts composition, the level of product adaptability is measured by the ratio of minimum number of parts that it theoretically could have to the existing parts that it currently has. The closer this measure is to 1, the better the product is perceived for adaptation. Evidently, this valuation assumes that a less complex product design is easier to adapt to the new environment. Mathematical representation for this computation is as follows:

$$\mu_{parameter} = \left(\frac{ideal\ \#\ for\ the\ parameter}{real\ \#\ for\ the\ parameter} \right) \qquad \text{Equation 7 [340]}$$

In addition, for upgrading/downgrading metric, the focus is placed on the efficiency of the product composition in executing its intended functions. The closer its architecture is to modularity, the better equipped the product is for adaptation. In this MAAP method, this evaluation is tailored to the requirements for product modularity that are outlined by Ulrich [326], which emphasize on the decoupling of product functions and interfacial relationships. The corresponding relationships are given as follows:

$$\mu FunctionalDecoupling = \left(\frac{\#\ Parts}{\#\ Functions\ per\ part} \right) + \left(\frac{\#\ Functions}{\#\ Parts\ per\ function} \right)$$

Equation 8 [340]

$$\mu InterfacialDecoupling = \left(\frac{real\ \#\ of\ decoupled\ links}{ideal\ \#\ of\ decoupled\ links} \right)$$ Equation 9 [340]

The suggested evaluation schemes for remaining metrics: remanufacturing, repair and maintenance; have also been detailed out in [339]. In short, these valuations are based on the work by Hammond and Bras [151] and the Pareto rule [330, 339]. Finally, each of the metrics is assigned with a weighting scale that indicates their relative importance to each other. The determination of this weighting value is done through the prioritization matrix that is depicted in Figure 38 for an example weighting case. This comparison is usually decided based on literature data or expert opinion [339].

	Remanufacturing	Maintenance	Repair	Up/Downgrading	Total Score	Weight (%)
Remanufacturing	1	5	0.2	1	7.0	21%
Maintenance	0.2	1	0.1	1	2.0	6%
Repair	5	10	1	5	21.0	62%
Up/Downgrading	1	1	0.2	1	3.0	9%
					33.7	100

Legend

10 (row)	requires much more investment than (column)
5 (row)	requires more investment than (column)
1 (row)	requires the same investment than (column)
0.2 (row)	requires less investment than (column)
0.1 (row)	requires much less investment than (column)

Figure 38: Assignment of MAAP Metric Weightings [339]

All in all, this MAAP method evaluates the aptness of product adaptation process in relation to its design architecture, where the main emphasis is on direct product reuse at the end of its operational lifecycle [147, 339]. It hypothetically covers all the important aspects of design adaptability but it should be realized that the metric values are best used in relative manner instead of taken as absolute [339]. Overall, this method is aligned with the scope of product redesign approach but it covers several aspects of product reuse that are unrelated to the conceptual redesign process. The repair and maintenance metrics, for instance, correspond to problems of broken or ineffective parts but such situation is not within the scope of the proposed SPEC method. Moreover, while it provides a good insight on how existing product design influences its adaptability, more consideration on how it performs for specific case of changes is required. The summarized advantages and disadvantages of this method are presented in Table 21 and its qualitative comparison to the desired characteristics for the proposed SPEC method is given in Table 22.

Table 21: Advantages and Disadvantages of MAAP

Advantages	Disadvantages
• Provide a clear definition of potential baseline assessment metrics • Assist the valuation of evaluation metrics • Provide a structured evaluation scheme	• Not directly applicable for specific engineering change assessment

Table 22: Qualitative Comparison of MAAP

Required SPEC Characteristics	MAAP
Provide a structured baseline evaluation scheme	★ (purple)
Suitable for considered scope of redesign process	★ (green)
Scalable to specific engineering change evaluation	★ (red)
LEGEND: ★ (black) Do Not Support ★ (red) Fair ★ (green) Good ★ (purple) Excellent	

3.1.4 Summarized Review of Baseline Assessment Methods

From this literature study, product evolvability criterion defined in the quantitative system evolvability method is taken as the best general measure for redesign. While there are several alternative definitions and various characteristics decomposition that can be linked to this characteristic, they essentially share a common basis. Overall, this criterion in the scope of product redesign can be described as its ability to be adapted towards new requirements, which will enable its prolonged service life or an extended application into new operational territories [147].

The potential competitive value and the importance in choosing the right baseline design, hence the capability to judge product suitability prior to its redesign development, has been clarified and supported by this literature review. The identified methods highlight various aspects that are useful in evaluating baseline evolvability characteristics. Even though none of them matches the desired functionalities to be directly applied in the proposed SPEC methodology, as indicated in Table 23, they nonetheless provide a good basis for the development of a structured guideline to measure product suitability for the redesign process.

Table 23: Qualitative Comparison of Identified Baseline Assessment Methods

Required SPEC Characteristics	Quantitative System Evolvability	SAF	MAAP
Provide a structured baseline evaluation scheme	★ (Fair)	★ (Fair)	★ (Excellent) [Best per criterion]
Suitable for considered scope of redesign process	★ (Good) [Best per criterion]	★ (Fair)	★ (Good)
Scalable to specific engineering change evaluation	★ (Fair) [Best per criterion]	★ (Fair)	★ (Fair)

LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent

Best per criterion

From the qualitative comparison presented in Table 23, MAAP is shown to have the best evaluation scheme. In fact, it is the only one among the identified methods that provides a structured assistance on the assignment of values for the evaluation metrics. However, the evaluation metrics proposed in the quantitative system evolvability method better capture the essences of redesign process considered in the scope of this thesis study. In terms of applying their evaluation procedure to the specific engineering change implementation case, all three methods perform comparatively at a similar level. The quantitative system evolvability method is given the extra edge since its evaluation metrics are closer to that considered for the redesign case.

3.2 Change Propagation Modeling

One of the main points that are deduced from the discussion in previous chapters is the importance for the product model to capture the essences of its change propagation potential. The planning for engineering changes during product redesign can benefit from a good understanding on how its realization affects other parts in the product architecture. Interrelationships between various product design elements have been recognized as the primary medium for change propagation [109, 116] and their identification is imperative for better coordination during product development [257, 273].

For any cases of redesign changes, interdependencies between product sub-modules that are either required, introduced or maintained during the process must be properly mapped out to locate exactly the initial modification and to track the likely paths of its effects propagation [152]. It is also essential to understand the behaviors of these direct or indirect links as the scale of required rework and cost for the development process highly depend on the propagated change effects [80, 187]. All things considered, an accurate depiction of product design architecture in terms of its change properties is necessary to estimate the side effects of its modification [259]. It was suggested that no matter how good the engineering change analysis is, its overall performance and accuracy heavily depends on the goodness of product change model [174].

From the outlined research questions in previous chapter, the literature review in this section is governed by the following subjects:

1) How engineering change effects propagate from one architecture locality to another?
2) What are control parameters of change propagation?
3) How to properly model aircraft system in order to predict change propagation?

Several modeling techniques have been developed in software engineering field for an automated tracking of program changes throughout its evolution, which normally involve breaking the computer program into manageable pieces and links them together through propagation graph [261, 281]. However, these methods are fairly inadequate for hardware product designs because the parametric links between physical parts are less explicit than those in computer program modules [80]. Unlike software products, change propagation in hardware products depends on the type of dependencies [273] and thus the necessary information about the interconnection needs to be included into the model. Despite the modeling phase being the most influential step in determining the overall efficiency of the process, it is preferred not to require too much commitment from product designers [165]. There has to be a well-balanced trade-off between the level of details and the cost of modeling [81]. In case of highly complex products like aircraft system, this balance between level of decomposition and amount of details is even more necessary [34].

Based on these arguments, several criteria have been outlined to compare the advantages and disadvantages of the identified system modeling methods for engineering change study. They are listed as follows:

(i) Provide a good change propagation tracking scheme
   a. Clearly define parameters involved in identifying potential change propagation paths
   b. Provide the means to predict and track change propagation paths

(ii) Provide a balance between level of details and cost of modeling
   a. Capture the essences of change propagation phenomenon in the model without imposing too much modeling commitment

3.2.1 Functional Change Modeling

Every product exists to accomplish a set of functions required by the customers and their raising expectations translates into improvement or creation of new product functions [347]. Accordingly, product design architecture can be perceived as an arrangement of functional elements in physical chunks that act as their building blocks [327]. The focus on design functions is suggested to be better for studying product variants development and reduced time-to-market production [282]. This is primarily because it enables a more flexible framework for exploring innovative design alternatives [257] and embodies a wide range of assumptions with respect to physical realization of the product [326].

In general, product functional modeling or else known as functional decomposition is the process of hierarchically breaking down high-level product functions into their lower sub-functions [192, 312]. This is "*an abstract, yet direct, method for understanding and representing an overall product or artifact function*" [159]. In many development cases, especially for complex engineered systems, this allows easier and manageable design analysis [196, 257]. The constructed functional platform is used as a basis for selecting physical product components and in redesign process, this platform is often established in the initial “reverse engineering” step. There are many available methods that can be used to model a product from its functional perspective. One of the identified modeling approaches is outlined by Stone et al. [312], which is illustrated in Figure 39 for a power screwdriver unit.

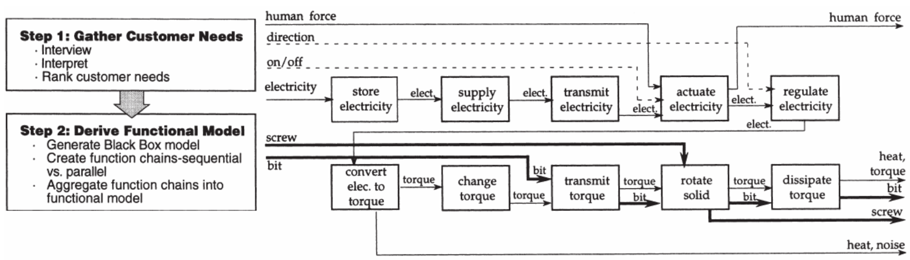


Figure 39: Functional Modeling of a Power Screwdriver [312]

From the standpoint of change study, the primary benefit offered by this functional model is the added information regarding interconnections between design parts that are often ignored by other methods. Apart from how the modification is realized, change effects propagation depends on the nature of the dependency between the affected design parts [273]. This information is helpful to predict the risk and level of the change impacts. In this model, the links are categorized into three classes of “flow”: energy, material and signal, which is passed throughout the product to form its functional structure [252, 312].

Nevertheless, the functional decomposition process is currently not uniquely defined and several different functional models could be created for the same product [192]. This is among the main reasons why functional modeling techniques are not widely utilized in product development process as it is hard to resolve any modeling conflicts without a definitive guideline [174]. To date, several works have been done to alleviate this issue, including hierarchical functional modeling technique by Bell [46] and identification of the best functional decomposition by Krishnamachari [192]. For this particular method by

Stone et al., a standard vocabulary known as “functional basis” has been specifically developed for the functional decomposition process [205]. This set of design language is aimed to regulate the model structure and to facilitate the streamlining of functional representation in order to resolve the inherent model inconsistencies. A full description of this “functional basis” is available in [159, 310]. Despite its introduction, this issue largely remains because “functional basis” is not yet taken as the universal standard for functional decomposition process.

Furthermore, since this functional model is not developed for engineering change study, it lacks the capability to directly support the assessment of propagated change effects or the implementation planning for required modification. Its main objective is focused on exploring different conceptual product architectures rather than working around a fixed baseline design [174]. In addition, its model representation rapidly grows for complex systems, which seriously hinders designers from tracking and analyzing potential change propagation paths. Additional efforts are also required for its graphical representation but they add nothing to the model applicability and efficiency for change process analysis.

On the whole, the advantages and disadvantages of this method are summarized in Table 24. Its qualitative comparison to the desired characteristics of product change modeling for the proposed SPEC methodology is given in Table 25.

Table 24: Advantages and Disadvantages of Functional Change Modeling

Advantages	Disadvantages
• Highlight potential change propagation paths through “flow” definitions	• Too much modeling efforts for features that do not help change study • Highly inconsistent process • Not readily usable for change study

Table 25: Qualitative Comparison of Functional Change Modeling

Required SPEC Characteristics	Functional Change Modeling
Provide change propagation tracking scheme	★ (Good)
Balanced model details and modeling efforts	★ (Fair)
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.2.2 Component-Function Propagation Model

In contrast to previous functional modeling, matrix-based modeling methods have the advantages of being more intuitive and require less effort in their model development [59, 174]. By far, these methods have gained a huge popularity in facilitating the analysis of relations for complex engineering systems. Different classifications of their application are discussed in [219]. The most common matrix-based modeling method is design structure matrix (DSM), which essentially originates from N^2 chart method [148].

DSM is traditionally applied to analyze project tasks and organizational development [219]. For this application, all activities, information exchanges and task dependencies in the project are translated into an interrelationship matrix [148] that is used to identify the personnel to be consulted or informed when any elements of the project has been changed [309]. The use of DSM is later extended to include product modeling and analysis; predominantly within the modular and platform design researches [125, 265]. At present, it has become a standard tool to model direct linkages or connections between two design elements [177]. So far, DSM models have been used in diverse industrial practices such as automotive, aerospace, telecom, electronics and other product industries [59].

The difference between N^2 chart and DSM model is mainly due to the fact that the latter representation includes the interdependencies of various subsystems beyond the physical interfaces. Depending on the intended level of model abstraction, the links could signify process characteristics, design parameters, and operational and functional dependencies [148]. The matrix configuration for product architecture representation in DSM modeling approach is illustrated in Figure 40 and it is crucial to understand the convention used for its construction. In short, any off-diagonal marks in the matrix signify that the element of the row is receiving input(s) from that designated by the column.

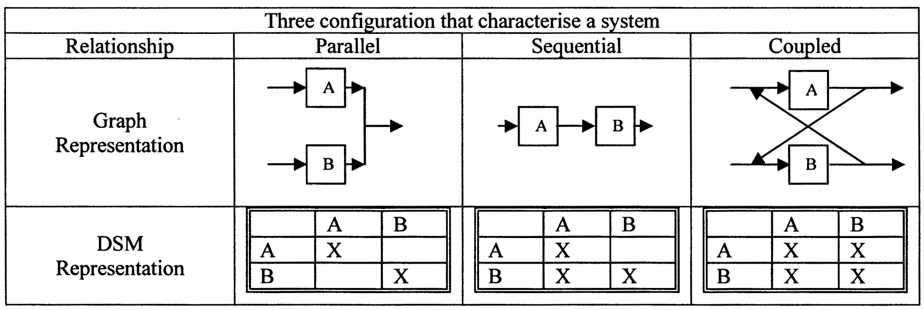


Figure 40: DSM Configuration for System Representation [148]

As can be observed from Figure 40, DSM model provides a simple and clear means to assess how change effects might propagate throughout the product architecture [81, 265]. Within the square matrix representation, product components or subsystems are identified by the headings of each row and column, and their dependencies are indicated by the off-diagonal marks [133]. It is assumed that these interrelationships are known prior to the initiation of this modeling process [64], which suits product redesign approach due to the well-defined state of the chosen baseline design. All in all, this DSM modeling is a well-established method that can provide a good aid in planning for product redesign process [60].

However, since the scope of interdependencies is broadened in this modeling technique, there are several key issues regarding the lack of guidance in the matrix construction for change study. A clear approach to construct the component dependencies in the product matrix model is required to avoid overlooked links that significantly reduce its efficiency to predict potential change propagation paths. This leads to the matrix-based modeling method proposed by Flanagan et al., which combines functional and physical aspects of the product system to guide the construction of the DSM model [134]. It should be noted that this "component-function propagation" model is developed specifically to assist the change propagation analysis, which makes it highly relevant for this research study. An overview of this modeling method is shown in Figure 41.

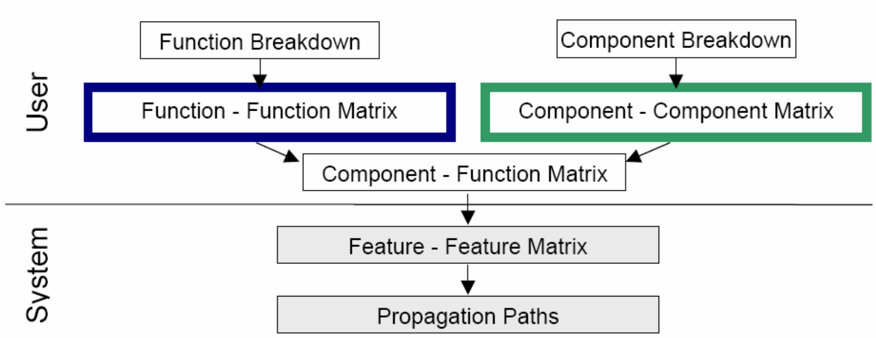


Figure 41: Component-Function Propagation Method [134]

In brief, the method starts with functional and physical decompositions of the product to obtain the function-function and component-component matrices, respectively. Function-function matrix is built based on the dependencies between the product functions while the component-component matrix is created to indicate physical interfaces between its physical components. These two matrices are combined based on the component-function matrix that relates the components to their intended functions. This combined matrix is called feature-feature matrix, which is basically a DSM with paired component-function as its rows and columns heading elements. Based on this matrix, the propagation paths can be tracked either from the initiating change of function or physical component. More detailed descriptions on this method are available in [134].

For this DSM modeling, the indication of interrelationships between the different parts or systems is not tailored to the directional flows of their inputs and outputs. This diverges from the traditional matrix-based modeling methods that have been previously discussed. Instead, each off-diagonal mark within this component-function propagation DSM model signifies an existing functional or physical connection between the system elements and it is assumed that this change relationship works in both directions. The latter criterion can be implied from the symmetric nature of the resultant feature-feature matrix. An example feature-feature matrix for a digger is shown in Figure 42. For this example, the shunting function of the bucket is the initiating change and the blue arrows show how one of the potential change propagation paths can be traced to the other affected parts.

	(A) Bucket/Shunt	(B) Arm/Shunt	(C) Bucket Hydraulic /Shunt	(D) Bucket Link/Shunt	(E) Arms/Raise Load	(F) Arm Hydraulic /Raise Load	(G) Bucket/Carry Load	(H) Arms/Carry Load	(I) Arm Hydraulic /Carry Load	(J) Bucket Hydraulic /Carry Load	(K) Hyd Pipes/Carry Load	(L) Bucket Link /Carry Load	(M) Bucket/Tilt	(N) Arms/Tilt	(O) Bucket Hydraulic /Tilt	(P) Bucket Link /Tilt
(A) Bucket/Shunt																
(B) Arm/Shunt	X															
(C) Bucket Hydraulic/Shunt	X	X														
(D) Bucket Link/Shunt	X	X	X													
(E) Arms/Raise Load																
(F) Arm Hydraulic /Raise					X											
(G) Bucket/Carry Load	X															
(H) Arms/Carry Load		X			X		X									
(I) Arm Hydraulic /Carry Load						X		X								
(J) Bucket Hydraulic /Carry Load			X				X	X								
(K) Hyd Pipes/Carry Load								X	X	X						
(L) Bucket Link /Carry Load				X			X	X		X						
(M) Bucket/Tilt	X						X									
(N) Arms/Tilt		X						X					X			
(O) Bucket Hydraulic /Tilt			X							X			X	X		
(P) Bucket Link /Tilt				X								X	X	X	X	

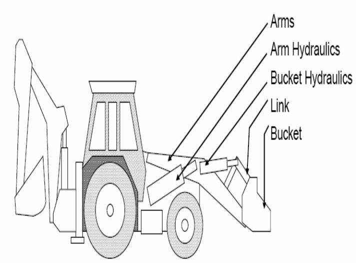


Figure 42: Propagation Path Determination in Feature-Feature Matrix [134]

It can be observed that this component-function propagation model provides a simple, yet clear and systematic visualization to track potential change propagation paths. This is a powerful aid for the change implementation planning. The model creation might be a time-consuming task [174] but it immensely assists in identifying all propagated effects from modifying any component within the architecture [265]. Moreover, from the way the model is constructed, the initiating change component can be identified by either its function or physical aspects.

On the other hand, one of the primary problems for this technique is the inconsistency of functional product decomposition [174]. The separately executed physical breakdown can lead to different level of details, which can cause problems during the combination of the function-function and component-component matrices. There has to be coordination between the two decomposition processes such that they both arrive at similar level of interrelationship details, which is not discussed in the reference sources. Furthermore, the deduction that any functional or physical link automatically represents a dual-way change relationship between the product components is misleading. In real product development practice, this is not always the case. Though a group of components might be responsible for the same high-level product function together, it is possible that the required changes only affect one of them. Similarly, the modification made in one component does not necessarily mean that all its other physically connected components also need to be changed. Hence the existing physical or functional relationship does not necessarily signify that the change effects will propagate from or to both components. Moreover, although the product model systematically helps to identify the potential propagation paths, it contains no additional information about the connection that can be used for change impact analysis. This omission becomes more crucial given the assumption of an automatic dual-way change relationship.

To summarize, the advantages and disadvantages of this method are summarized in Table 26. Its qualitative comparison to the desired characteristics of product change modeling for the proposed SPEC methodology is given in Table 27.

Table 26: Advantages and Disadvantages of Component-Function Propagation

Advantages	Disadvantages
• Clear and systematic change propagation tracking • Manageable modeling efforts	• Can be an inconsistent process without proper coordination between decomposition processes • Misleading assumption of change interrelationships • Not readily usable for change study

Table 27: Qualitative Comparison of Component-Function Propagation

Required SPEC Characteristics	Component-Function Propagation
Provide change propagation tracking scheme	★ (Good)
Balanced model details and modeling efforts	★ (Good)
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.2.3 Component Linkage Model

In an effort to avoid the issues associated with inconsistent functional decomposition process, Jarratt proposed a modeling technique based on the observed links between parts of the product [174]. These links, or better known as component linkages in this method, are defined as a direct relationship or connection between two individual parts, sub-assemblies or modules of the product [176]. They can be a physical connection or a functional association [176], and their interrelationships can be symmetrical or one-way directional [174].

The main difference between component linkage analysis and functional analysis is that the former method starts with physical product decomposition. By knowing the specific physical components, their relationships can be deduced in a broader scope than just the functional connections. For instance, the connection between two parts due to a shared manufacturing process can also be represented in this model [176]. The heart of this modeling method is essentially the DSM representation and the steps involved in its execution are depicted in Figure 43.

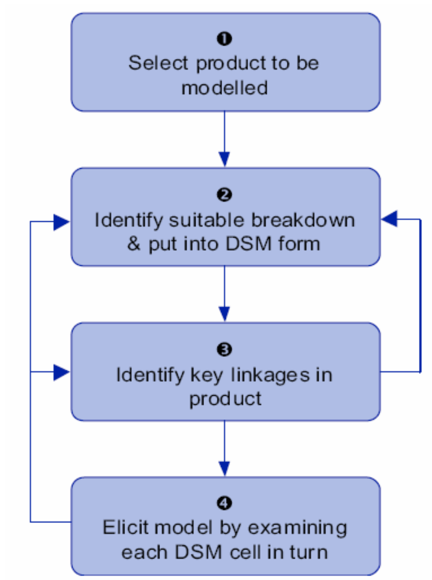
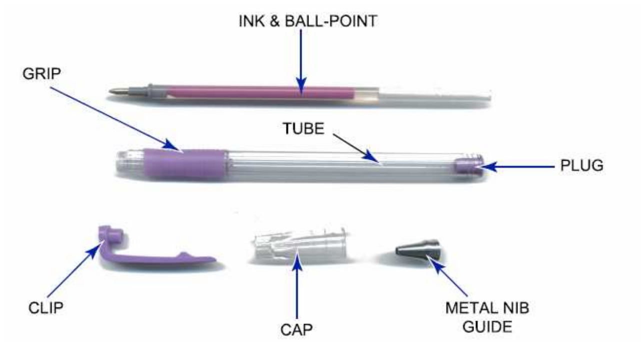


Figure 43: Product Linkage Modeling Method [174]

In short, the interested product is first physically decomposed until the required level of details is reached. Next, types of linkages related to the interested product analysis are identified. Besides the product operational or architectural dependencies, any issues or problems from the past change process can also be considered [174]. Finally, the last step is to identify the interconnections between the components for each type of linkages. Additional information on the type, likelihood of change propagation and level of change impacts can be included later into the model. The process can also be reiterated to re-decompose the product for a better illustration or to include additional linkage types to increase the details of the resultant DSM model.

To illustrate this method, an example of linkage modeling for a ball point pen is shown in Figure 44. As can be observed, four types of linkages are defined for the model. Based on information in Figure 44, the pen model can be constructed. This is shown in Figure 45, where each linkage type is represented by a separate DSM model. In typical change process analysis, a combined DSM model is often used with the change likelihood and impact values inserted in place of the "X" marks. It is proposed that these values are tailored to the modified FMEA scheme as tabulated in Table 28.



Linkage	Definition
Mechanical	parts are physically, joined or held together
Spatial	there is a need for adjacency or orientation between parts
Material	parts are fabricated from the same material
Colour	parts are the same colour

Figure 44: Ball Point Pen Linkage Modeling [174]

Mechanical Links	Plug	Tube	Grip	Ink & b-pt	Nib guide	Cap	Clip
Plug		X					
Tube	X		X	X	X	X	
Grip		X					
Ink & b-pt		X			X		
Nib guide		X		X			
Cap		X					X
Clip						X	

Spatial Links	Plug	Tube	Grip	Ink & b-pt	Nib guide	Cap	Clip
Plug				X		X	
Tube							
Grip						X	X
Ink & b-pt	X					X	
Nib guide						X	
Cap	X		X	X	X		
Clip			X				

Same Material Links	Plug	Tube	Grip	Ink & b-pt	Nib guide	Cap	Clip
Plug							X
Tube						X	
Grip							
Ink & b-pt							
Nib guide							
Cap		X					
Clip	X						

Colour Links	Plug	Tube	Grip	Ink & b-pt	Nib guide	Cap	Clip
Plug			X	X			X
Tube							
Grip	X			X			X
Ink & b-pt	X		X				X
Nib guide							
Cap							
Clip	X		X	X			

Figure 45: DSM Representation for Linkage Models [174]

Table 28: Modified FMEA Rating for Change Likelihood and Impact Measure [176]

Likelihood of Change Propagating	Impact if Change Propagates
0: No Propagation	0: No Impact
1: Very Low	1: Very Minor
2/3: Low	2/3: Minor
4/5: Moderate	4/5: Moderate
6/7: High	6/7: High
8/9: Very High	8/9: Very High
10: Propagation Inevitable	10: Complete Redesign Required

By including the linkage types and the measures of change likelihood and impact level, this linkage modeling provides additional information that is useful for change impact analysis. The use of DSM model representation enables this method to obtain the benefits of a matrix-based model. Moreover, as the method focuses on existing components and builds the relationships around them, it is highly applicable to product redesign process [174]. The linkage definition can be easily tailored to the required information for the subsequent change impact analysis, which increases its application flexibility.

Nevertheless, while the component linkage model includes change propagation likelihood and impact measures into its combined DSM representation, information on the type of linkages or the current change situation is not considered in populating these measures. Instead, their values are often derived based on previous product modification [174]. Since these measures are not tailored to current product redesign process, their values can mislead the subsequent analysis process. In other words, if these values are used to evaluate the overall risk for the proposed changes, the analysis is readily biased towards past change targets and ignores the effects of change type and level that currently have to be handled [273]. A more level and unbiased method to populate these change likelihood and impact values is thus required.

On the whole, the advantages and disadvantages of this method are summarized in Table 29. Its qualitative comparison to the desired characteristics of product change model for the proposed SPEC methodology is given in Table 30.

Table 29: Advantages and Disadvantages of Component Linkage Model

Advantages	Disadvantages
• Clear and systematic change propagation tracking • Manageable modeling efforts • Include useful change information for impact analysis • Readily usable for change study	• Information included is based on past change data

Table 30: Qualitative Comparison of Component Linkage Model

Required SPEC Characteristics	Component Linkage Model
Provide change propagation tracking scheme	★
Balanced model details and modeling efforts	★
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.2.4 Change Favorable Representation (C-FAR)

Recognizing that the change propagation depends on the type of changes made on the initiating part, Cohen et al. introduced change favorable representation (C-FAR). Its main objective is to set up a data representation that aids designers in making product modification and tracking its propagated effects [83]. The modeling process is done in EXPRESS, a programming language that assist product definition through its in-built modeling schema [11, 83]. An overview of the relationships between this C-FAR method and EXPRESS is available in [82].

In short, C-FAR aims at tracing and predicting change propagation by identifying the interactions between the attributes of the product elements [80, 176, 273]. Each physical part of the product is modeled as a vector and their attributes are taken as components of that vector [83]. The influence of a change made on one component attribute to that of others is captured in the C-FAR matrix. This change interrelationship is supplemented by the scale of their strength (i.e. high, medium or low) based on expert opinions [42, 45, 106]. An example model is shown in Figure 46.

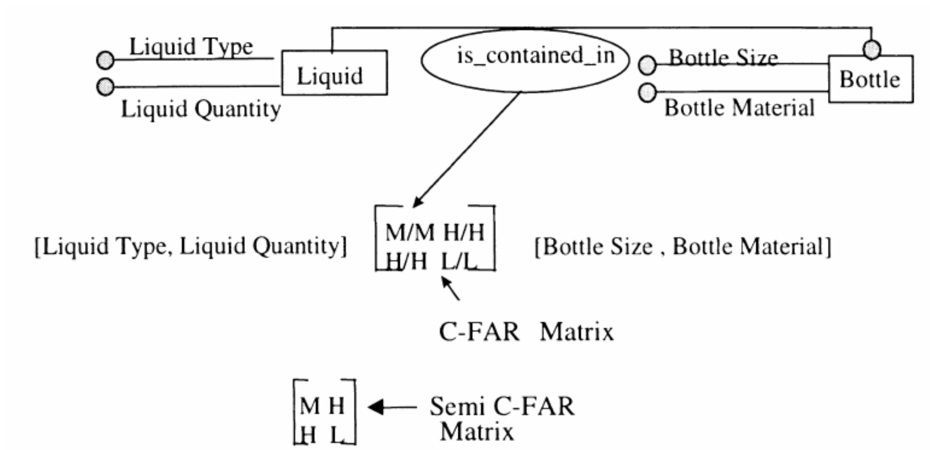


Figure 46: C-FAR Product Representation [83]

In this sample case, two interested entities involved in the design of a bottle are the liquid and the bottle itself. Both are supplemented with two attributes each, which are related to each other in the C-FAR matrix. The rows represent the attributes of the liquid while the columns refer to those of the bottle. Value for the first matrix element corresponds to the influence strength of the liquid attributes on those of the bottle whereas the second value indicates the reverse. For instance, the second row and first column element of the full C-FAR matrix shows the connection between liquid quantity and bottle size. The “H/H” entry implies that the liquid quantity highly influences the bottle size and vice versa. Note that the matrix can also be reduced into a semi C-FAR matrix representation, which only shows one way relationship. Component attribute that initiates a change is identified along with the interested target attribute and the change propagation path from the former to the latter is derived based on the populated C-FAR matrix. A numerical scale is used to represent the level of connection strength during the calculation of propagated effects, which is detailed in [83].

Overall, this modeling method captures the necessary factors to predict propagated change effects; which are change type and magnitude. This is a big improvement over other modeling approaches for change process. However, it does not provide a structured plan on how these measures should be derived. The likelihood of change propagation and the required amount of redesigning efforts are often assigned with the average over their past occurrences regardless of the actual change made in the initiating component [273], which can lead to inaccurate change propagation analysis. The main focus of this method is the representation of product data information rather than change implementation [82] and this explains the lack of emphasis on the valuation of its measures.

In addition, its model build-up is rather complex and subjective, where the identification of component attributes that can influence and be influenced by others appears to be rather time-consuming, especially for complex products. Since the propagation path is automatically generated based on C-FAR matrices, any overlooked attributes could affect the overall evaluation. On opposite side of the argument, too many attribute declarations lead towards heavy calculation. Its computational complexity and required modeling efforts makes the application of this method only appropriate for small and relatively simple products [80, 184]. Furthermore, this method only supports the analysis of change propagation from one attribute to the specified other. This restricted capability makes it inefficient to handle the product redesign process, where multiple initiating changes are usually defined and their propagated effects can interact with each other. Due to its model definition up to component attribute levels, it is possible that a required change will affect more than one attribute of the same component but this condition is not captured by the C-FAR matrix.

The advantages and disadvantages of this method are tabulated in Table 31. Its qualitative comparison to the desired characteristics of product change modeling for the proposed SPEC methodology is given in Table 32.

Table 31: Advantages and Disadvantages of C-FAR

Advantages	Disadvantages
• Clear and systematic change propagation tracking • Include useful change information for impact analysis • Readily usable for change study	• Modeling efforts can be rather tedious for complex products • Information included is based on past change data

Table 32: Qualitative Comparison of C-FAR

Required SPEC Characteristics	C-FAR
Provide change propagation tracking scheme	★ (purple)
Balanced model details and modeling efforts	★ (red)
LEGEND: ★ (black) Do Not Support ★ (red) Fair ★ (green) Good ★ (purple) Excellent	

3.2.5 Product Dependency Model

In similar principle to previous C-FAR modeling method, Rutka et al. proposed product dependency model. However, instead of the complicated model build-up like the former method, this product dependency model uses DSM representation structure. Its scope of application is also expanded to include other development process characteristics apart from the product design.

In brief, the dependency model between product components is based on three criteria as listed below [273]:

1. Contain information that represents several viewpoints or domains of the engineering system such as requirements, product architecture, design process or activities
2. Contain additional dependency information that describes the interconnection between two items from the same or different domains
3. Able to be evolved as the overall design representation matures

A sample product dependency model is illustrated in Figure 47. Each item included in the DSM model representation belongs to one of the identified domains, which could be design requirement, product component or design task. Items in the matrix are equipped with a set of attributes that describes the nature of their interdependencies, as listed in Table 33. A key attribute included in this product model is the process milestone when the affected component is no longer allowed to be modified. In such cases, the initiating change component have to contain the otherwise propagated effects within itself. This attribute accounts for circumstances when the part design is “freeze” after it has reached certain stages of product development lifecycle. The choice to “freeze” components is normally determined by the company’s regulation or process requirements.

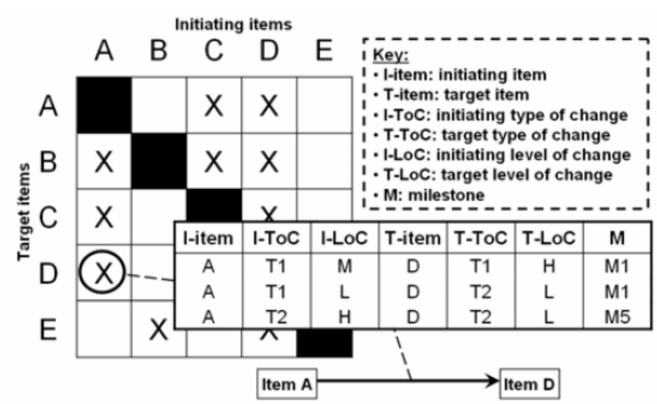


Figure 47: Dependency Modeling [273]

Table 33: Item Descriptive Attributes

Attribute	Description
I-item	the component that initiates the change propagation
I-ToC	the type of the initiating change
I-LoC	the required amount of rework caused by the initiating change
T-item	the component that is receiving the propagated change effects
T-ToC	the type of change effected on the target item
T-LoC	the required amount of rework imposed on the target item
M	the process milestone when the target component is frozen and not allowed to change

Referring to Figure 47, the matrix is read from column to row. The expanded descriptive attributes table corresponds to the included information for element in column A and row D. For instance, reading first line of the table, a modification of type T1 in item A will cause a propagated change of type T1 on item D. Depending on the modification level, the level of propagated effects will also be different. The first line indicates that if item A is changed with M level, then the effects on item D is T1 at level H. However, for the same T1 change on item A with level L, the propagated effect on item D is of type T2 at level L. Furthermore, if the change occurs after the M1 milestone of the product lifecycle, no propagated effects will be imposed on item D and item A has to be modified to match this condition.

On the whole, this product modeling method improves the change analysis by including more complete data on how the initiating changes can propagate to other components. This facilitates a better indication of possible propagation paths. In retrospective, this is similar to some of the benefits offered by C-FAR but they are achieved here with much simpler modeling efforts. The inclusion of the process milestone attribute also better matches the real product development process. However, no mention of a structured plan on how the measures of change likelihood and level of impacts can be derived is provided. It is then assumed that they will be based on historical change data.

In conclusion, the advantages and disadvantages of this method are tabulated in Table 34. Its qualitative comparison to the desired characteristics of product change modeling for the proposed SPEC methodology is given in Table 35.

Table 34: Advantages and Disadvantages of Product Dependency Model

Advantages	Disadvantages
• Clear and systematic change propagation tracking • Include useful change information for impact analysis • Manageable modeling efforts • Readily usable for change study	• Information included is based on past change data

Table 35: Qualitative Comparison of Product Dependency Model

Required SPEC Characteristics	Product Dependency Model
Provide change propagation tracking scheme	★ (Excellent)
Balanced model details and modeling efforts	★ (Good)
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

<u>3.2.6 Summarized Review of Change Propagation Modeling Methods</u>

Many authors agree that the DSM model provides a simple, yet clear visualization on the possible propagation of change effects within the product architecture through its simple square matrix representation [59, 81]. This can be inferred from the inclination of many product modeling techniques to employ it as their representative structure. Despite the fact that DSM model can become very large and hard to analyze for complex systems, it is perhaps the current best representation for product change study at the moment [293]. It is certainly a well-established technique that can act as a basis in planning for product redesign process [60].

Through their works, Pimmler and Eppinger demonstrated that a complete interaction pattern for system architectures can be adequately illustrated using these matrix-based methods [257]. Although the basic DSM model does not include any information on the propagation likelihood or the level of change effects, these values can be easily added once the interconnections between the parts have been established. It should be noted that good redesign decisions require an understanding of the process risks and opportunities [97] but it has been argued that the current valuation scheme for these parameters is often biased towards past changes and thus can be misleading. Since designers can be pushed into a specific decision space by the biasness of their methods and tools [306], a proper care must be taken to improve the way these measures are derived.

On the other hand, there also seems to be a disagreement as to how the modeling process is better approached. Authors such as Schaz [282] and Pimmler and Eppinger [257] had advised that the functional approach is more suitable but Jarratt disagreed and proposed that the focus is put instead on physical components [174]. In general, all engineering design involves form and function: "*there is no form without function and no function without physical manifestation*" [134] and their interaction actually prompts the change propagation [298]. Depending on the problem interest, functional approach can be a better choice than physical approach, and vice versa. For product redesign, the available knowledge about the baseline should be exploited as maximum as possible to guide the change planning. Because the existing physical components indicate available redesign freedom, the physical approach by Jarratt is more reasonable for this study. However, another main problem that exists in current product modeling for the engineering change study is the absence of a proper guideline on the balance between the development efforts and the level of details to be included in the model [34, 81]. Not all product components or aspects is necessary for change propagation analysis [174] and it is important to have the right set of information for manageable model size, especially for complex products.

Depending on the requirements of analysis tasks, the level of product details and hence the model size need to be aptly controlled.

Based on this literature study, summary assessment of the identified product modeling techniques to the desired criteria for the proposed SPEC method is shown in Table 36.

Table 36: Qualitative Comparison of Identified Change Propagation Models

Required SPEC Characteristics	Functional Change Modeling	Component-Function Propagation	Component Linkage Model	C-FAR	Product Dependency Model
Provide change propagation tracking scheme	★ (Good)	★ (Good)	★ (Excellent)	★ (Excellent)	★ (Excellent) (Best per criterion)
Balanced model details and modeling efforts	★ (Fair)	★ (Good)	★ (Good)	★ (Fair)	★ (Good) (Best per criterion)

LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent
[shaded box] Best per criterion

From the qualitative comparison presented in Table 36, product dependency model is shown to have the overall best characteristics among other identified product models for the scope of change study covered in the proposed method. This is mainly due to its simple construction and complete change information for the impact analysis.

3.3 Change Impact Analysis

The most critical phase of engineering change process is the impact evaluation for the implemented product modification [176]. This can be implied from the emphasis of many available standards in product manufacturing industries. Unfortunately, none of these standards provides change impact analysis method or tool as part of their guidelines [273]. Before the modification can be analyzed to decide whether their implementation is acceptable, their system-wide effects such as total efforts in planning, scheduling and resourcing have to be predicted [152].

In general, this section is focused on addressing the following research questions:

1) What are characteristics of an aircraft and its development process that can be affected by engineering changes?
2) How to sufficiently measure change impacts on these characteristics?
3) How to manage overall aircraft redesign risks?

From this literature study, available methods and tools for change impact analysis in software engineering are found to be arguably more advanced than those in other product fields. Nonetheless, the key difference between software and mechanical products is that the latter performance is highly influenced by the geometries of their physical parts [232]. The parametric links between their parts are less explicit [80] and the propagation of their change effects highly depends on the type of interdependencies [273]. This condition makes most methods and tools in software development rather inappropriate for use in hardware development. Nevertheless, while they cannot be directly applied to analyze the change impacts on hardware products, their process frameworks can be a good reference.

The dynamic requirements and the fast advancement pace of software market subject most computer programs to frequent modification [336]. Similar to hardware product industries, more software programs are being redesigned than newly developed and this is indicated by the usual 70-30 ratio of maintenance-to-development research expenditure within the software community [201]. The "maintenance" here refers to the necessary changes on existing computer programs. In view of this, the importance of change impact process is shared between the software and hardware product development. Based on his research in Butler Cox Productivity Enhancement Program (PEP), Moreton outlined the general process framework for change management in software engineering [237]. This workflow ranges from identifying the change needs, analyzing its full impacts on the system, implementing it once approved and updating the associated documentation [216], as illustrated in Figure 48. From this framework, the main elements of change impact that need to be focused on are costs and amount of reworks required by the modification.

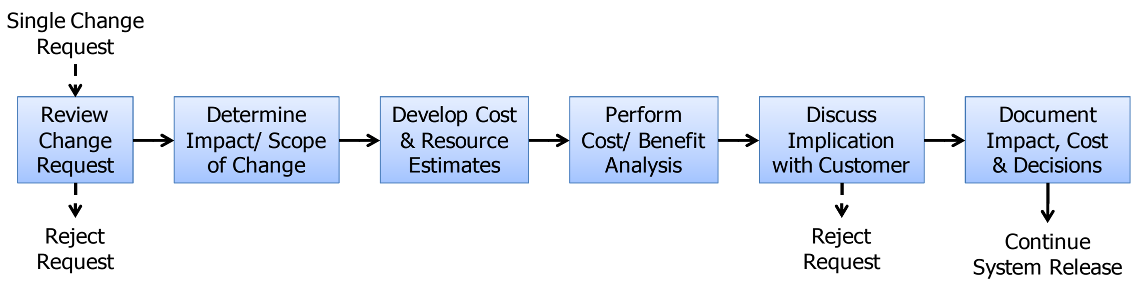


Figure 48: General Impact Analysis Step in Software Change Management [237]

The change impact analysis is undeniably a crucial step to the effectiveness of the overall change planning process. Making strategic planning decision requires the overall problem outlook as change effects for the product sub-areas might be connected to each other [334], which depends on the applied methods or tools to provide the required information for the assessment purposes [211]. Generally, the primary goals here are to trace and analyze the dependencies involved during change propagation [41]. Based on knowledge gained up until at this point, several essential criteria of the methods or tools that properly capture engineering change impact analysis as intended for the SPEC method can be outlined as follows:

(i) Capture the essences of possible change impacts

   a. Clearly define evaluation metrics to assess change impacts

   b. Simultaneously cover both product and process impacts

(ii) Provide a structured evaluation scheme for change impact assessment

   a. Provide a clear evaluation method for identified metrics

  b. Support the evaluation of impacts from simultaneous change propagations

(iii) Provide assessment scheme that is representative of the change task

  a. Utilize unbiased change information for impact analysis

From the background studies, available change impact methods that are identified to be relevant to this research study are discussed as follow.

3.3.1 Change Propagation Analysis (CPA)

This qualitative change propagation evaluation method is proposed by Rutka et al. and it is tailored to the product dependency model as described in section 3.2.5. In this method, the prospect of change propagation is derived through simple Boolean dependencies that are based on the information of their dependency strength and the required type and level of the changes [273]. The simulation of change effects starts with the specified initiating item and the program algorithm is outlined to identify all interdependencies that are related to it. In cases when the change type and level are specified, the identified item with matching labels will become the next initiating item in the propagation path. This path tracking procedure is continued until the propagation reaches its stopping criterion.

To better demonstrate this method, an example of a simple propagation tree is depicted in Figure 49 that demonstrates three end conditions for the algorithm. Item A here is the change initiating element and once modified, it propagates the change effects to items B, C and D. However, since item D is classified as “frozen”, this path is terminated and item A has to absorb whatever change effects that it initially tries to propagate to item D. For the other change paths, when item B is modified, it further propagates the effects to item E. The path stops here as item E is not interconnected to any other items. Last but not least, by changing item C, the change effects are propagated back to items A and B.

However, since item B has already been affected by item A at a higher level of impact, it will not be allowed to change again if the type of change is similar to that previously imposed. For this algorithm, a lower or similar level of the same type of modification is assumed to be covered by the previously imposed higher level change. On the other hand, by changing item A again, it will trigger the same propagation tree all over again. To avoid endless change effects propagation, the computing algorithm is set with a stopping criterion when a previously changed item is encountered again. Alternatively, an external counter can also be set to limit the number of allowable propagation steps.

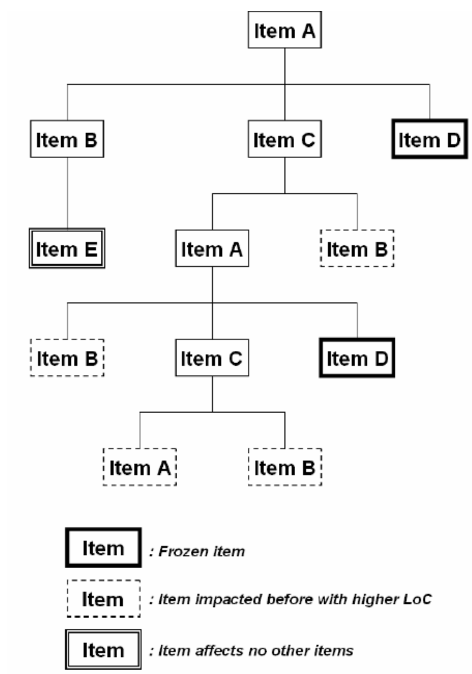


Figure 49: Simple Change Propagation Tree [273]

Once all propagation paths have been mapped out, the risks related to the decision criteria such as cost, time and other is analyzed. In this method, the final level of change defined for all affected items in the propagation tree dictates the maximum value for their specific type of change and the risk calculation is dependent on this change impact level and its likelihood [273]. A combined risk value for the decision criteria, also called global risk, is then derived by combining that of the individual item.

Overall, this method provides a clear scheme on how the propagated change impacts can be mapped and evaluated. The use of product dependency model allows an accurate and efficient tracking of the propagation paths, and the stopping criteria applied in the change propagation algorithm highlights the various component roles in the propagation tree. In addition, the risk analysis is done as a post-processing step after the paths have been determined and this allows it to require minimal computational power as opposed to include the analysis into the main algorithm itself [273]. The downsides of this method are the facts that it does not detail the specific way to evaluate the measures of the risks and does not consider the process with simultaneous initiating changes.

To summarize, the advantages and disadvantages of this method are tabulated in Table 37. Its qualitative comparison to the desired criteria of change impact analysis for the proposed SPEC methodology is given in Table 38.

Table 37: Advantages and Disadvantages of CPA

Advantages	Disadvantages
• Capture complete essences of change impact factors • Allows consideration of both product and process parameters	• No assistance on assignment or evaluation of change impacts

Table 38: Qualitative Comparison of CPA

Required SPEC Characteristics	CPA
Capture the main essences of change impacts	★
Clear evaluation scheme for impact assessment	★
Representative of the change task at hand	★
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.3.2 Progressive Change Probabilities

An identified disadvantage of many change propagation techniques is their assumption of constant probability across the propagation tree. Since the propagated change effect also depends on change likelihood of previous component in the tree, its probability should be cascading from top to bottom of the product structure [160]. Alternatively said, in a multi-level product structure, component commonalities have the potential to affect the change likelihood for lower-level items depending on how they are interconnected to the initiating part or component [160]. This change likelihood estimate is used to calculate the measure of change risks, which makes it important to have a reasonable prediction of its value. In the product risk management field, the risk model is estimated as the product of change likelihood and scale of impacts that the change will produce [80, 176].

Ho and Li proposed an analytical procedure to calculate the progressive probability of an engineering change for a part or component within multi-level product structures. Their computation is based on several assumptions on the change propagation [160]:

- Lower level parts or components will not cause obsolescence or propagate change effects upstream
- The need for propagated changes from multiple higher level component are independent to each other

In general, computation for the progressive change probabilities is given as follows:

$$P_{EC}(j) = P_j + \sum_{i-1}^{j-1} P_{EC}(i) \times P_{ji} \qquad \text{Equation 10 [160]}$$

$$P_{ji} = \begin{cases} 0 & \text{if item } i \text{ is not an immediate parent of item } j \\ 0 & \text{if engineering change of item } i \text{ will not cause changes on item } j \\ C_{ji} & \text{otherwise}, 0 < C_{ji} < 1 \end{cases}$$

where: $P_{EC}(j)$ the probability of engineering changes imposed on item j, $j = 1,2,\ldots,n$

P_j the probability of engineering changes for item j without considering engineering changes of higher level items

P_{ji}, C_{ji} the conditional probability of engineering changes for item j resulted from engineering changes in item i

An example case is presented to illustrate this computation, which is shown in Figure 50.

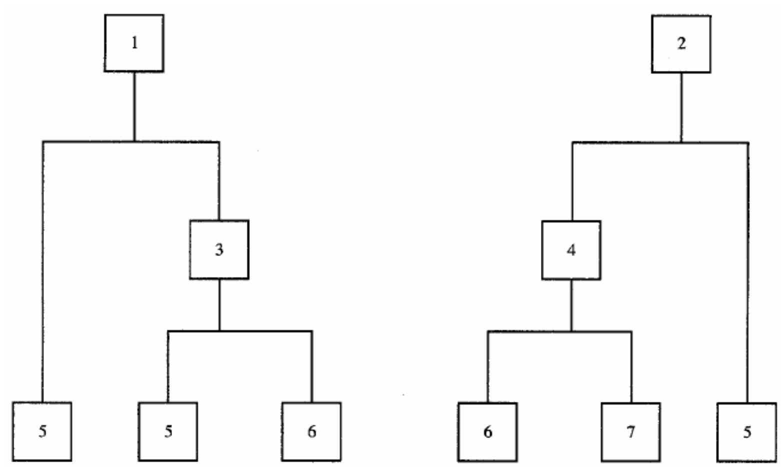


Figure 50: Example Product Structure for Progressive Change Probabilities [160]

Based on the governing assumptions, change propagation flows only from top to bottom of the tree structure. Furthermore, item 5 has three different immediate parents: items 1, 2 and 3. Following the second assumption, the change propagation effects from all of them are taken to be independent of each other. The calculation of change likelihood on item 5 is then given as follows:

$$P_{EC}(5) = P_5 + \left[(P_1 \times P_{51}) + (P_{EC}(3) \times P_{53}) + (P_2 \times P_{52}) \right]$$

Overall, this method only outlines the analytical computation of the progressive change likelihood. There are no other elements to assist the change impact analysis is included or discussed. Furthermore, the restrictions imposed by its underlying assumptions limit its practical use. For many complex product systems, engineering change effects are often propagated in both directions between two components. In addition, it is impossible to impose a hierarchical structure for engineering change process without prioritizing some components over the others, which obviously leads to a biased change analysis.

In conclusion, the advantages and disadvantages of this method are tabulated in Table 39. Its qualitative comparison to the desired criteria of change impact analysis for the proposed SPEC methodology is given in Table 40.

Table 39: Advantages and Disadvantages of Progressive Change Probability

Advantages	Disadvantages
• Clear outline of change likelihood estimation	• No definition of change impact parameters or evaluation metrics • No detailed method to assess change impacts

Table 40: Qualitative Comparison of Progressive Change Probability

Required SPEC Characteristics	Progressive Change Probability
Capture the main essences of change impacts	★ (black)
Clear evaluation scheme for impact assessment	★ (red)
Representative of the change task at hand	★ (black)
LEGEND: ★ (black) Do Not Support ★ (red) Fair ★ (green) Good ★ (purple) Excellent	

3.3.3 Response Surface Method (RSM) in Change Impact Assessment

While the computing technology has been significantly improved over the years, the level of complexity for disciplinary design computational programs remains the stumbling block for a faster design evaluation or verification. The required high computation times for these design models restrict the amount of program evaluations that can be fit into the available timeframe during the early phases of design process [265]. In similar fashion, the initial evaluation on the effects of product modification can take a long time when the planning of the changes is being constructed. Since the change effects can determine the success or failure of a product redesign development, it is rather imperative to be able to estimate their potential impacts during the redesign planning to identify all design trade-offs that are involved [314].

In their quantitative requirements traceability method, which establishes the connections between product requirements and their inflicted design changes, Sutinen et al. used response surface method (RSM) to quantify the estimated change effects early in the development process [265]. In short, RSM is applied to approximate complex computational design model by creating a simpler empirical meta-model of the process that allows a faster change impact evaluation procedure. The meta-model is statistically developed from relative contribution of the input variables to the interested system response, and this knowledge is obtained from analyzing the experiments or simulations that have been constructed from design of experiments (DoE) technique [191].

The meta-model from this RSM method is known as response surface equation (RSE) and it is often taken to be of a second order polynomial shown as follows:

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon \qquad \text{Equation 11 [191, 265]}$$

where R = response of interest, b_0 = intercept term, b_i = regressed coefficient term for linear terms, b_{ii} = regressed coefficient term for pure quadratic terms, b_{ij} = regressed coefficient term for cross-product terms, x_i, x_j = input variables of interest, ε = error term associated with the second order approximation

Once the RSE is available, it can be used in place of complex analysis codes to study the quantitative engineering change impacts from the proposed modification. It should be noted that this method is extremely useful when the change impact analysis is backed by several simulation studies [265]. For aircraft system design application, this method has been demonstrated in several works, most prominently to this change study is its use in Technology Identification, Evaluation and Selection (TIES) method by Mavris et al. [228]. In that application, the RSEs are used to quantify different impacts of technology implementation on aircraft performance properties.

On the whole, RSM can be taken as a powerful method to quantitatively estimate change impacts during product redesign planning. The estimation of possible impacts from the changed design is supported by the determination of relative contribution of the modified parameters to the interested metrics. Its applications in product development process such as TIES for aircraft system demonstrates its capability to capture the change effects on redesigned product performances, instead of just the development process characteristics like most change impact analysis methods. However, it should be noted that the accuracy of its prediction depends on the approximation errors of the RSE that must be kept very small to have meaningful impact estimation. The meta-model development can be very time-consuming if the computer-based analysis or simulation codes are unavailable and the application of each model is limited within the defined output and inputs boundaries [265]. The advantages and disadvantages of this method are presented in Table 41 and its qualitative comparison to the criteria of change impact analysis for the proposed SPEC method is given in Table 42.

Table 41: Advantages and Disadvantages of RSM in Change Impact Assessment

Advantages	Disadvantages
• Provide means to quantitatively estimate change impacts • Assist screening of impact parameters based on their relative contributions on evaluation metric	• Development of meta-model can require significant efforts • Need to be aligned with change process to have meaningful results

Table 42: Qualitative Comparison of RSM in Change Impact Assessment

Required SPEC Characteristics	RSM in Change Impact Assessment
Capture the main essences of change impacts	★
Clear evaluation scheme for impact assessment	★
Representative of the change task at hand	★
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.3.4 Summarized Review of Change Impact Analysis Methods

Engineering changes can simultaneously affect both product and its development process. Having this in mind, it is essential to have proper means to predict these two categories of change effects. In general, the main objective of change impact analysis is to estimate the extent of effects from the proposed product changes, which can help in deciding the most proper redesign plan [170].

In many change support methods and tools that have been identified during this literature study, change impacts are often measured in terms of the process risks involved. By the definition from risk management field, change risk is qualitatively estimated as a product of change likelihood and scale of impacts that it will produce [80, 176]. Nonetheless, very few studies are focused on examining change effects on the product, especially for complex, multi-level product structure [160]. It is known that the modification affects the product performance and the exclusion of this aspect from the impact analysis is a serious oversight. Typical change methods only consider the impact of changes on cost factors but not so much on time, solution flexibility or quality of the redesigned product [142]. This situation is mainly due to the fact that the disciplinary evaluations are usually very time-consuming and require tremendous efforts to be executed during the change analysis process. One promising method to cope with this problem is RSM. By approximating the meta-model that represents the high-fidelity analysis codes, computation can be made in a faster pace than having to run the simulation study every time a product element is changed. Bear in mind that if the meta-model has to be constructed through manual experimentation, it might still take too much time and efforts. Nonetheless, there is a high need to ensure that the changes do not affect the product's capability to perform to its operational requirements, both new and existing ones.

Moreover, an unbiased scheme to account for the possibilities of propagated changes and their impacts is required. In general, their measure can be made either qualitatively or quantitatively. Although the qualitative approach is generally less precise, its results can be obtained much faster than the parametric formulas in quantitative approach [273]. This choice basically depends on the assessment objective. For the proposed SPEC method, its main objective is to compare and select the best change implementation plan among the potential alternatives. It is clear that this is a relative assessment problem and qualitative measurement is rather adequate for this method.

To summarize, although none of the identified change impact analysis methods perfectly matches the outlined functionalities to be directly applied in the proposed SPEC method as indicated by Table 43, they provide invaluable information for the construction of a better method to assess the consequences of engineering changes.

Table 43: Qualitative Comparison of Identified Change Impact Analysis Methods

Required SPEC Characteristics	CPA	Progressive Change Probabilities	RSM in Change Impact Analysis
Capture the main essences of change impacts	★ Excellent (best per criterion)	★ Do Not Support	★ Fair
Clear evaluation scheme for impact assessment	★ Fair	★ Fair	★ Fair (best per criterion)
Representative of the change task at hand	★ Fair (best per criterion)	★ Do Not Support	★ Fair

LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent
Best per criterion

From the qualitative comparison in Table 43, CPA has the better method that captures the essences of change effects and its definition of evaluation metrics considers both product and its development process. However, it lacks a structured guidance on how the metrics should be evaluated. On contrary, while the use of RSM for prediction of change impacts needs to be tailored to the change process characteristics, it offers a straightforward scheme on how to appropriately calculate the evaluation metrics. Therefore, it is taken to have the best evaluation scheme among the identified methods, assuming the appropriate simulation analysis tools are available.

3.4 Change Implementation Planning

At first glance, the implementation of a product modification might deceptively seem like a simple task. However it often ends up being more complicated once the actual redesign process is executed. The study in Westland Helicopters revealed that their most difficult and costly redesign projects are actually those associated with design retrofits, which often appear rather straightforward during the initial planning [80]. It is very rare that the changes made on one component does not affect the others [267], especially for complex products [273]. Hence the change initiator or implementer is responsible to be aware of all potential propagated effects to decide on the right trade-offs during planning of the modification [83]. In addition, many redesign cases involve several initiating changes and their effects can be interconnected [67, 174, 218]. According to Han, changes can be implemented independently or concurrently only if their driving factors have been clearly outlined [152]. Prioritization for these changes can also be predetermined [134].

On the whole, based on these various elements of change implementation process, a good redesign strategy is required as to how the knowledge of possible risks and impacts can be used to create a better product modification plan. In general, this section is focused on addressing the following research questions:

1) What are important criteria for a good change implementation plan?
2) What are control parameters that are available in change planning?
3) How to generate implementation plan for the required changes?
4) How to select the best change implementation plan among possible alternatives?

The importance of change propagation and impact analyses has been emphasized by the discussion from previous sections. A reliable change propagation tracking is key to the success of product redesign planning [187] as it requires full knowledge of the possible downstream process [78]. Nevertheless, because engineering change has been perceived negatively within the design process, there is a clear lack of support tools and methods when it comes to assisting designers in strategically planning for the best change implementation. Even if the management of the driving requirements and the derivation of the proper product model have been accomplished, there is often little or no support at all for generating the change implementation alternatives and selecting the best proposal [36]. The information obtained from the change propagation and impact analyses is often only applied to assess redesign risks at the high process level. Jarratt stated that many research efforts in this engineering change field have been individually pursued and thus the application of resultant methods and tools have yet to be streamlined together [174]. This situation needs to be resolved to enable a better product redesign planning solution, which is important because the decisions made during early design stages, for example, can determine as much as 70% of the overall product costs [318].

Based on this realization, as well as the arguments made in previous chapters, several criteria are outlined to compare the advantages and disadvantages of the identified tools and methods for redesign planning. They are listed as follows:

(i) Provide a structured redesign strategy
   a. Proper use of change information in planning
   b. Include proper expert interactions in the process

(ii) Provide a proper redesign plan assessment scheme
   a. Define proper metrics to evaluate alternative plans
   b. Define a structured scheme for plan selection

(iii) Scalable to simultaneous initiating changes case
   a. Allow concurrent planning of several change implementations

3.4.1 RedesignIT

RedesignIT is essentially a computer-based tool that is constructed based on the concept of model-based reasoning to generate and evaluate product redesign proposals [246]. The causal reasoning defined between identified physical quantities of the product design is the main element that is used to plan for its modification [176]. In general, the primary application of this RedesignIT tool is to help product designers plan for required changes during the initial stages of the redesign process. Based on the inputs of performance targets by the user, it will automatically generate the best modification plan in accordance to the change interrelationships defined in the product model [247].

Operating principles of RedesignIT tool can be briefly described as follows. First of all, the product model is constructed. Design parameters in the model are divided into two categories: target quantities and exogenous quantities. The setting of the target quantities, which is allowed to either be maximized or minimized, is the translation of the design goals that need to be accomplished [246]. To achieve specified redesign goals, the setting for exogenous quantities is varied accordingly to generate possible combination of change plans. These potential design change plans are ranked based on their degree of accomplishing the goals, nature and severity of the side effects to aid designer in making the selection. To better illustrate the concept behind this tool, an example case of a four-stroke, turbocharged diesel engine is shown in Figure 51. Note that this representation details have been reduced for better illustration.

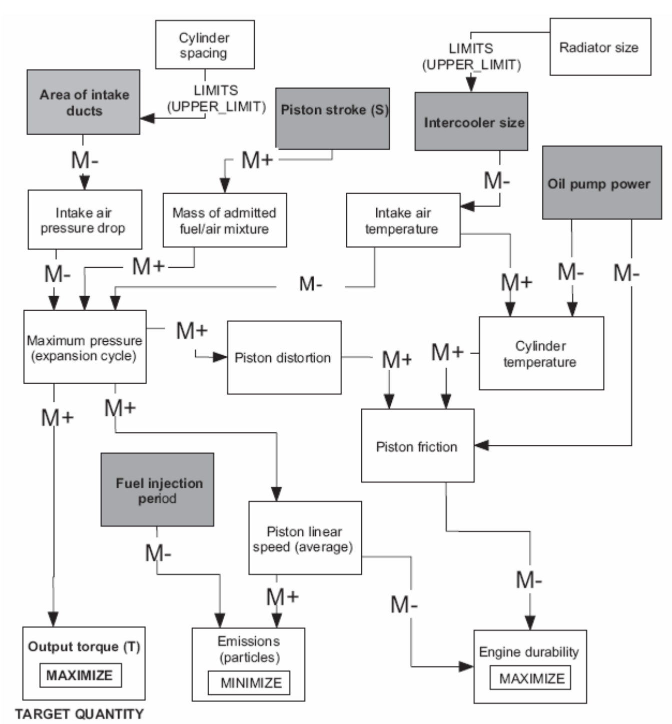


Figure 51: A Four-Stroke, Turbocharged Diesel Engine Model [247]

Assume that the main goal for the engine redesign is to have a larger output torque. When initiated, the program will search for all possible ways to achieve this target. This leads to the increment of piston stroke, intercooler size or area of intake ducts, as can be observed in Figure 51. However, the latter two options have a constraint condition that opposes the intended modification and therefore, the piston stroke is selected as the initial change. By increasing the piston stroke, it also causes changes to several other quantities such as an increase in fuel/air mixture and a reduction of engine durability. The program algorithm then automatically searches for the necessary changes to counter these undesirable side effects. This process will eventually be terminated when there is no more exogenous quantity that could be changed, even if the undesired side effects are not yet entirely eliminated.

It can be seen that the concept behind its execution really takes into account the strategic redesign planning. Product model to be used with this tool does not require accurate numerical inputs but instead, it qualitatively works with information regarding the nature of the causal relationship, the direction of the monotonic relationship and the qualitative magnitude of the association [247]. It can be noted that the principles of causal reasoning is applied to generate the behavior of possible change propagation [247, 289]. In addition, the notion of exogenous quantities is based on Keller et al. [188, 247] while the concept of qualitative simulation is based on Kuiper et al. [194, 247].

On the other hand, although the product model does not entail numerical input values, it requires a thorough understanding of the physics behind the product design construction. It is rare that “design rationale” information is properly documented in available PDM or PLM packages [36]. This could be a problematic situation as designers are required to have thorough understanding of overall product aspects, which is impossible for complex products like an aircraft system. The situation can be remedied by having the inputs from related experts across the development process but that increases the required modeling time and efforts. In addition, to allow for a better assessment of change likelihood, it is necessary to include an indication of the magnitude for the causal relationship on top of their monotonic direction [247]. This is emphasized during the discussion on available change propagation modeling techniques.

In addition, the model also limits the application of redesign process since it assumes that the product architecture will essentially remains the same after the redesigning effort. This can be implied by the way the exogenous quantities are defined in the model, which is static throughout the process. This restriction is a big disadvantage and needs to be improved as most redesign projects often involve notable design deviations from the baseline product architecture. As stated by Han, change methods should consider the possibility that the applied engineering changes will introduce new sub-modules into the architecture instead of limiting their analysis capability on only changes that can be made to static product modules [152]. Moreover, the causal reasoning algorithm can also lead towards unnecessary changes while trying to counter the emerging side effects from the primary modification. There is no “check and balance” process to analyze the trade-offs between accepting the negative side effects that might not even be significant enough to cause the product to fail its performance constraints and incorporating additional changes to resolve them. This drawback goes back to the limitations due to product model and change propagation tracking. Ultimately, this creates a high possibility that the added costs and efforts could exceed those that would have been incurred by directly fixing the affected component.

Finally, the concept behind this redesign strategy is goal-directed. This indicates that the redesign objective has to be translated into available target quantities within the product model before the process can be executed. However, the redesign process involves more than just high-level system performance requirements. The cases of specific component replacement due to new technology implementation based on customer preferences are not applicable for this tool since no target quantities in the product model directly capture this kind of change motivation. Plus, the automated generation of redesign plans has no interaction with designers and the redesign planning decision is solely based on the goal of satisfying all target quantities regardless of the risks or efforts involved.

To summarize, the advantages and disadvantages of this method are tabulated in Table 44 and its qualitative comparison to the desired criteria of change planning analysis for the proposed SPEC methodology is given in Table 45.

Table 44: Advantages and Disadvantages of RedesignIT

Advantages	Disadvantages
• Provide a structured and automated redesign planning strategy • Works without requiring an accurately numerical change model • Generate best redesign plan that satisfies target goals • Consider simultaneous change implementations	• No experts interaction • Do not consider redesign risks involved with proposed modifications • Potentially entail extra modeling efforts

Table 45: Qualitative Comparison of RedesignIT

Required SPEC Characteristics	RedesignIT
Provide a structured redesign strategy	★ (green)
Provide a proper redesign plan assessment scheme	★ (green)
Scalable to simultaneous initiating changes case	★ (purple)

LEGEND: ★ (black) Do Not Support ★ (red) Fair ★ (green) Good ★ (purple) Excellent

3.4.2 KRITIK

KRITIK (a Sanskrit word that can be translated as "the designer") is a design support tool that contains 17 processing modules that correspond to typical tasks involved during the product development process [143]. These include procedures for design retrieval, design adaptation, design storage, candidate-design selection and others. It integrates case-based and model-based reasoning principles to derive a new product by adapting the existing design that has the closest characteristics to the target requirements [145]. In KRITIK, the design modification process is taken as a task of gathering necessary information regarding the deficiencies of the baseline design in comparison to the target specifications and based on the differences, changes on some parts of its structure that could make its performance closer to the desired target are proposed [69]. According to Goel and Craw, KRITIK was the first autonomous design system that fully addressed case-based design tasks [144].

The heart of this KRITIK program is the structure-behavior-function (SBF) model that is constructed from the knowledge of causal behaviors that map the product structure to its intended functions [145]. In this perspective, a product system will be represented by the components, the substances (i.e. energy and material flow) and the relationships between them, which describe the specific behavioral state of the product design. Moreover, the function is treated as a transformation link from one behavioral state to another that explains how physical elements of the product achieve their designated functions [217]. This information is utilized by KRITIK to plan for the required changes when the output of the behavioral state (i.e. current product capability) differs from the target [68]. In brief, KRITIK's modification-generation procedure is illustrated as in Figure 52.

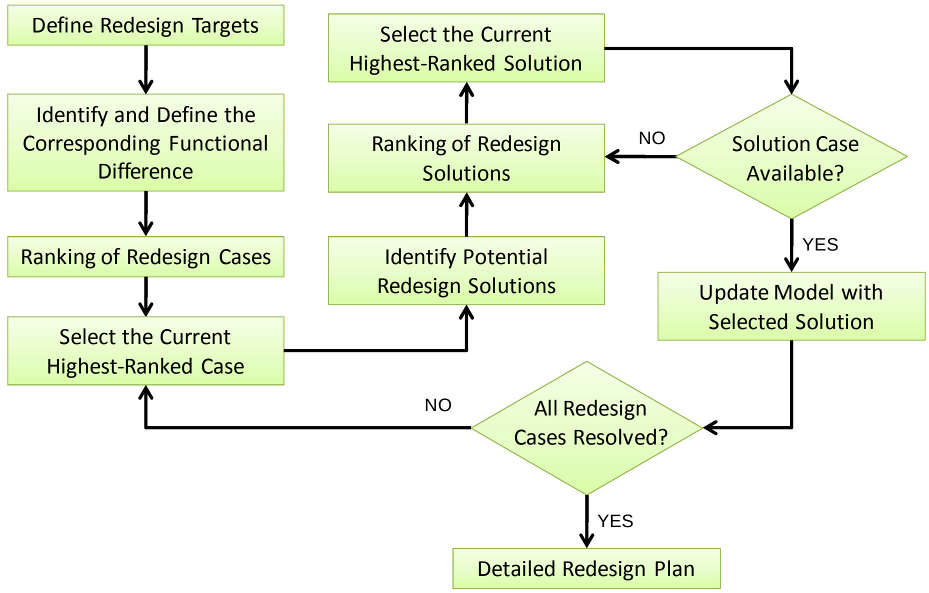


Figure 52: Summarized Redesign Procedure in KRITIK

The process starts with a clear definition of the desired functionalities or the modified target requirements. Based on the product's SBF model, its affected functions that will be considered for the modification process are identified. Next, the differences of its current functional metrics to the targets are established. In cases where more than one functional difference needs to be considered, they are ranked based on their difficulty level, with the most difficult one to be resolved is given the highest priority and considered first. Based on the underlying causal reasoning for the function in SBF model, possible modifications to achieve the specific target can be derived. If more than one possible way to redesign the product is available, the potential modifications are heuristically ranked according to their execution difficulty. The program then searches through its database to find whether a known solution that matches the proposed change is available. If not, this program will abandon the candidate modification and pursue the subsequent highest-ranked alternative plan. Before the start of next redesign cycle for the subsequent functional difference case, the model states are updated with the selected modification. The process ends when all functional differences have been resolved.

On the whole, this tool captures many essences of a strategic product redesign planning particularly the concurrent initiating changes situation. By ranking the required redesign tasks according to their difficulties and updating the system model before a new cycle of modification planning is executed, it provides a structured scheme to simultaneously plan for the necessary changes and avoid major conflicting effects.

Nevertheless, there are also a few setbacks that can be associated with this method. Due to its case-based nature, the redesign plans are constrained by known solutions that are available in the database. The basic principle behind case-based design methods is to solve the current problem by retrieving and adapting the closest past solution [143]. It relies on the analogy to the past problem that can provide some insights on how to solve it [217]. Accordingly, the pool of possible change solution is limited to the stored cases. Moreover, the redesign process is executed here with the assumption that each function can be localized to certain parts of the product, which corresponds to a specific design case. However, this concept of design case is hardly applicable to many complex product structures as it is difficult to isolate the designs into totally independent areas of decision-making [217]. In such cases, the existing relationships between different “case” plans are overlooked during their individual planning process and this situation can affect the overall performance metrics. Generally, this makes its application rather limited to small, simple engineering devices [144]. Additionally, its redesign focus on the functions might be a problem to accommodate physically-motivated changes and it also ignores other essential evaluation metrics for change plan such as its risks and costs. Finally, with similar argument to the modeling disadvantages of RedesignIT, the SBF model requires thorough understanding of the physic-based principles behind the product design in order to extract all causal relationships between its components. This require high modeling efforts since most PDM or PLM systems are not equipped with such information storage [217].

On the whole, the advantages and disadvantages of this method are tabulated in Table 46 and its qualitative comparison to the desired criteria of change planning analysis for the proposed SPEC methodology is given in Table 47.

Table 46: Advantages and Disadvantages of KRITIK

Advantages	Disadvantages
• Provide a structured and automated redesign planning • Do not require an accurately numerical change model • Generate best redesign plan that satisfies the target goals • Consider simultaneous changes implementation	• No experts interaction • Do not consider redesign risks involved with proposed modifications • Constrained by the efficiency of the case database • Potentially entail extra modeling efforts

Table 47: Qualitative Comparison of KRITIK

Required SPEC Characteristics	KRITIK
Provide a structured redesign strategy	★ (Good)
Provide a proper redesign plan assessment scheme	★ (Good)
Scalable to simultaneous initiating changes case	★ (Excellent)
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.4.3 Change Prediction Method (CPM)

This Change Prediction Method (CPM) is conceived to assist designers in planning their product redesign development process and incorporating the assessment of change effects propagation into consideration [80, 176]. Through its procedures, the redesign decision-making process is supported by the provision of estimated risks that the modification in one component will affect the others within the existing design architecture [187]. Based on two numerical DSMs that contain the measures of change likelihood and impact for each identified dependencies between the product components, the risks for making the initial change is qualitatively quantified [273]. The illustration of this method is shown in Figure 53.

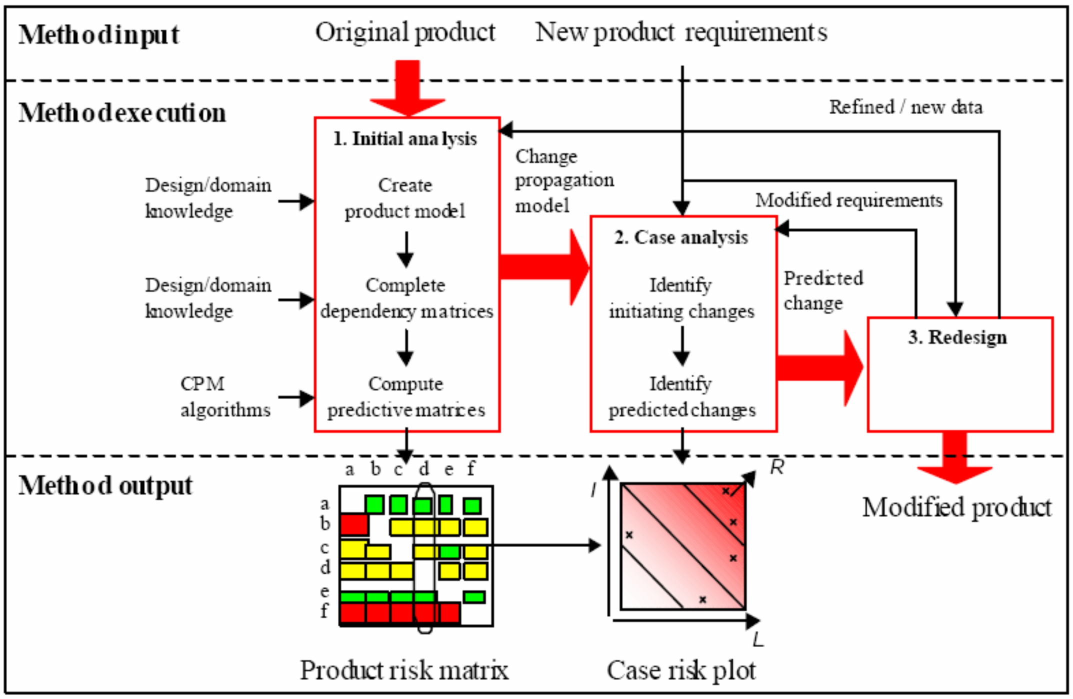


Figure 53: Change Prediction Method [80]

In short, the method starts with an initial analysis step. In this phase, the product model is created through its decomposition process. A well-balanced product model in terms of its level of details and cost of populating it is preferred, and the suggested rule of thumb is to consider only 50 or less components [80]. Once the components have been identified, their interrelationships are mapped into the DSM and each of them is assigned with their predictive measure of propagated change risk. An internal algorithm will compute the change risks using these values and the results are populated in the product risk matrix. The representation of this risk matrix follows the concept of risk graph by Coppendale [80, 91], which is shown in Figure 54. Basically, the top right-hand corner is the highest risk area where the propagated change is indicated to be highly possible and its impacts are very detrimental to the development process. The color coding utilized in Figure 54 to describe the risk level is explained as follows: red (high risk), yellow (medium risk) and green (low risk). After that, the initiating modifications from the driving requirements are identified and the predicted change propagation paths due to their implementation into the product are automatically generated. The associated risks for the generated plans can be calculated from previously computed risk matrix and the decision to accept them is made by considering the amount of risks involved. This process can be re-iterated until a satisfactory redesign plan is derived.

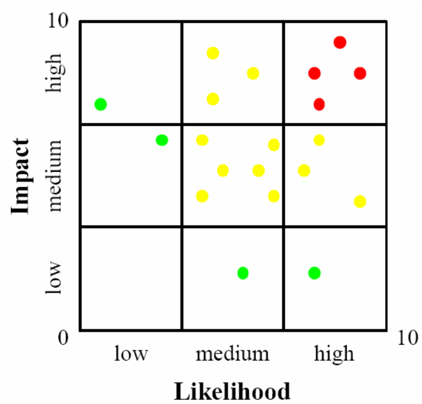


Figure 54: Sample Representation of Risk Graph [80]

An important concept in this method is the estimation of propagated change risks. A simple risk model that is defined as a product of change likelihood and scale of impacts that it will produce is adopted here [80, 176], which is adapted from product risk management field [13, 80]. In general, the measure of change likelihood is estimated by the average probability that changes on a component will propagate to the other based on its occurrence during past redesign cases. On the other hand, the change impact measure is valued in reference to the amount of necessary reworks when the component is affected by the propagated changes. These two measures are normalized within a scale from 0 to 1. A sample calculation for the direct change risk is demonstrated in Figure 55.

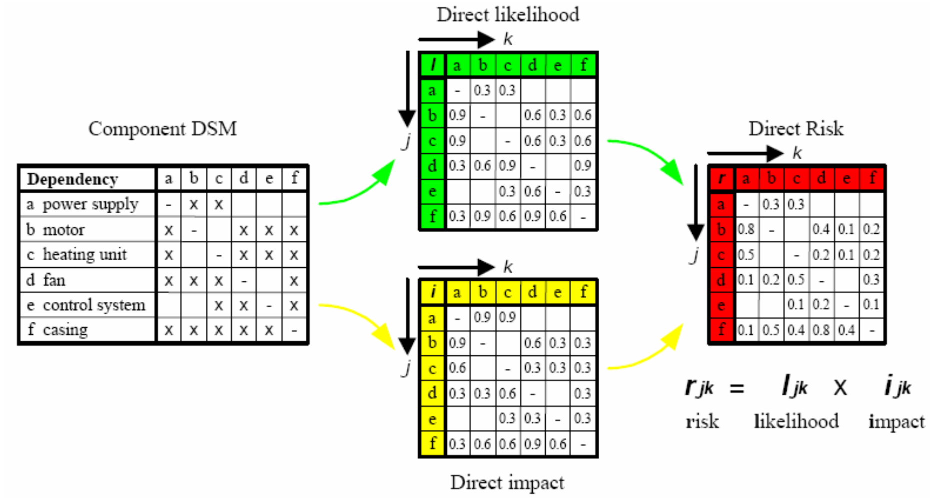


Figure 55: Direct Propagated Change Risk Calculation [80]

Besides the direct effects, there are also indirect change impacts. It is of high interest to be able to evaluate the total risks from both direct and indirect propagated change effects during redesign planning process. Here, the calculation of combined change risk is described using an example case shown in Figure 56, which is assumed to represent all possible change propagation paths in the sample product design architecture.

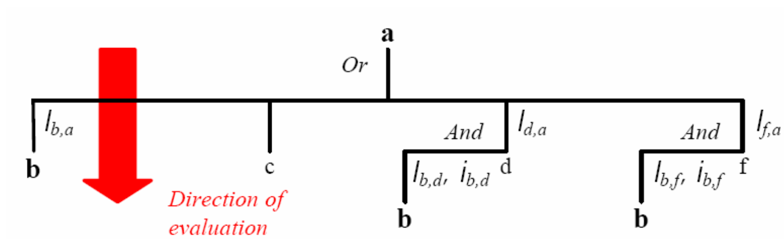


Figure 56: Example Case for Combined Change Propagation Risk Calculation [80]

To calculate the combined risk for change propagating from component *a* to *b*:

$$R_{b,a} = 1 - \prod (1 - \rho_{b,u}) \qquad \text{Equation 12 [80]}$$

$$\rho_{b,u} = \sigma_{u,a} l_{b,u} i_{b,u} \qquad \text{Equation 13 [80]}$$

where: $R_{b,a}$ combined risk of change propagation from *a* to *b*

$\rho_{b,u}$ direct risk of change propagating from all intermediate components *u* that link between *b* to *a*

$\sigma_{u,a}$ likelihood of change propagation from *a* to *u*

$l_{b,u}$ direct likelihood of change propagating from *u* to *b*

$i_{b,u}$ direct impact of change propagating from *u* to *b*

Therefore, based on Figure 56:

$$R_{b,a} = 1 - \prod \left(1 - \rho_{b,u}\right) = 1 - \left[\left(1 - \rho_{b,a}\right)\left(1 - \rho_{b,d}\right)\left(1 - \rho_{b,f}\right)\right]$$

$$R_{b,a} = 1 - \left[\left(1 - l_{b,a} i_{b,a}\right)\left(1 - \sigma_{d,a} l_{b,d} i_{b,d}\right)\left(1 - \sigma_{f,a} l_{b,f} i_{b,f}\right)\right]$$

$$R_{b,a} = 1 - \left[\left(1 - l_{b,a} i_{b,a}\right)\left(1 - l_{d,a} l_{b,d} i_{b,d}\right)\left(1 - l_{f,a} l_{b,f} i_{b,f}\right)\right]$$

It was suggested by Rutka et al. that CPM is evidently one of the most advanced change propagation method that is presently available [273]. The output of this method can be used to aid designers in planning for the least risky product modification to satisfy the imposed requirements. According to Clarkson et al., the relative success of this method in the industry lies in its use of only generic information but the powerful application of its outcomes [80]. It should be known that several assumptions have been incorporated into the computing algorithm for the combined change risk. Since the propagated engineering change effects can return back to the initial modified component and thus creates possible endless loops of propagated effects, the limit is set to three or four propagation steps [80]. This simplification is backed by the notion that change probability rapidly decreases with propagation steps and thus will not have significant impacts in comparison to the ones calculated in earlier steps. This has been demonstrated to be a valid assumption with a sample application on a helicopter redesign process [80].

However, even with this simplification, the amount of required computational efforts can rapidly increase for large product model [175, 273]. A Monte Carlo-based calculation method is proposed to remedy this problem. In this new estimation approach, the problem is further simplified. The probability of change propagating from one component to the other connected components is assumed to be mutually exclusive to each other, which means that only one propagation path can be selected. This turns the change propagation problem into a series of "random walk" [175]. To ensure that the probability is mutually exclusive to each other, the probability of selecting none of the potential propagated paths is added and they are all normalize to the total probability. It has been demonstrated that this probabilistic approach arrived to mostly the same conclusive results as the ones obtained from the original CPM but with much less computational time [175].

Despite its usefulness in assisting product designers in planning the engineering change implementation, there are also several drawbacks of this method. First of all, although it highlights the propagation paths and the risks associated with them, no direct redesign planning strategy is involved during the automated generation of redesign plan [120]. The complete specification of the change plan is automatically generated by a computer algorithm based on the predicted change propagation tree without any decision inputs from designers. Furthermore, the change likelihood and risk definitions used in this method are too broad to capture the essences of change propagation. How a component is affected by the changes will depend on the modification of the preceding component in the propagation path [80]. However, the automated change propagation algorithm in this method does not formally consider such details [265, 273]. It relies heavily on the estimated inputs based on previous change experiences [120, 175, 265], which can lead to a biased evaluation of the process. Moreover, according to the reference literature, the required changes are independently analyzed in this method [265] and hence the decision to implement them is based on separate tradeoffs that could easily overlook their possible interactions. Many product redesign problems deal with more than one required initiating change and their effects are interconnected with each other [120, 272, 332]. However, it should be noted that not all change processes need to be considered simultaneously when they are totally independent of each other. Last but not least, this method also requires a high computational effort for the analysis of large, complex products. Though the Monte Carlo-based approach has been introduced to alleviate some of these problems, its probabilistic calculation still need a much clearer guidance on how certain parameters are being defined. For instance, the distribution for change propagation likelihood or that for the change risks needs to have a good basis of definition, which is not clearly outlined in the reference literature.

Overall, the advantages and disadvantages of this method are tabulated in Table 48 and its qualitative comparison to the criteria of change planning analysis for the proposed SPEC methodology is given in Table 49.

Table 48: Advantages and Disadvantages of CPM

Advantages	Disadvantages
• Provide a structured and automated redesign planning • Works with a simple risk model • Provide selection of change plans based on their risks	• No experts interaction during generation of the change plans • Risk evaluation can be misleading due to high reliance on past change data • Consider initiating changes separately during planning • Can be computationally expensive

Table 49: Qualitative Comparison of CPM to Desired Criteria

Required SPEC Characteristics	CPM
Provide a structured redesign strategy	★ (Good)
Provide a proper redesign plan assessment scheme	★ (Excellent)
Scalable to simultaneous initiating changes case	★ (Good)
LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent	

3.4.4 Summarized Review of Change Planning Methods

Based on above discussion, it can be seen that most change methods do not include any implementation strategy in their routines. As stated by Clarkson et al., a high reliance is put on the past experiences of product design experts to manually try to minimize the change effects [79]. In addition, most available methods rely heavily on historical data that can lead to a biased change propagation analysis. Since the characteristics of engineering changes can differ from case to case, taking the average historical measure to estimate the change likelihood and impact metrics without considering the differences in change problem scenarios can mislead the overall risk evaluation. Depending on the type and level of executed changes, the probability for change propagation phenomenon can be affected differently. In decision-making process, the information provided through computer tools highly influences user's choice of action [305]. Thus it needs to be ensured that the provided decision aids are truly reflective of the actual process.

Han suggested that an automated change propagation analysis should be applied only in cases with well-defined and static product structures [152]. As can be observed, most automatically generated change plans assume that physical product components in the existing architecture will remain the same as it is before the proposed initial modification. This is not always true as some revolutionary changes can take place and consequently modify the dynamics between the components. For instance, if a pump unit is modified, the automated redesign algorithm can only capture the changes in the magnitudes of its already defined parameters. To change from a pneumatic pump to an electrical pump, for instance, is definitely out of its capability as to predict the subsequent propagation paths. Also, most of these algorithms do not take into account the concurrent handling of the initiating engineering changes. Unless the effects on the various initiating components are completely independent such that their propagation paths will never cross each other, their interactions have to be considered during planning. By evaluating them separately, their combined effects can be overlooked and this can be a crucial omission during risk analysis.

To summarize, although none of the identified change implementation planning methods exactly matches the outlined functionalities to be directly applied in the proposed SPEC method as indicated by Table 50, all of them can be used as solid references.

Table 50: Qualitative Comparison of Change Implementation Planning Methods

Required SPEC Characteristics	RedesignIT	KRITIK	CPM
Provide a structured redesign strategy	★ Good	★ Good	★ Good (Best per criterion)
Provide a proper redesign plan assessment scheme	★ Good	★ Good	★ Excellent (Best per criterion)
Scalable to simultaneous initiating changes case	★ Excellent	★ Excellent (Best per criterion)	★ Good

LEGEND: ★ Do Not Support ★ Fair ★ Good ★ Excellent; shaded cell: Best per criterion

From the qualitative comparison in Table 50, CPM is evaluated to have a slightly better method in exploiting the proper change information to generate and evaluate plans for change implementation. Their use of risks measure is considered the most relevant to decide on redesign plans, even though the risks in terms of product performances should be added for a complete assessment. It should also be stressed that none of these methods includes any interaction with designers while generating the change plans and this is the main deficiency that needs to be improved. For concurrent handling of initiating changes, the ranking scheme in KRITIK is considered as the most structured procedure.

3.5 Other Enabling Techniques and Definitions

Based on previous discussion on available change methods and tools, several areas of improvements to match their capabilities to the intended characteristics of the proposed SPEC methodology have been recognized. Further literature reviews have been done to discover several enabling techniques or standard definitions that are well-recognized in the industry to close these gaps. Improvements that are considered as urgent for this research study can be categorized into following areas of concentration:

- Derivation of a change impact assessment scheme
- Derivation of a change propagation prediction scheme

As can be concluded from previous sections, an unbiased scheme to account for the possibilities of propagated changes and their impacts is required. This is important to ensure the integrity of the assessment results, which will also affect the redesign decision made based on them. The measures can be assigned either qualitatively or quantitatively. Although qualitative approaches are less precise, their results can be obtained much faster than the parametric formulas in quantitative approaches [273]. This choice basically depends on the assessment objective. For the proposed SPEC method, its main goal is to compare and select the best change implementation plans among the possible ones. It is apparent that the assessment is comparative in nature, which indicates that the qualitative measurement is also adequate for the process.

3.5.1 Qualitative Change Impact Measurement

To enable change impact analysis, the measure of predicted level of effects from the modification has to be included into the product change model. However, during this modeling stage, no information is yet available on the required modification. Without any information on the specific change type and level that will be made, the assignment of change impact level has to be based only on the interconnection type and the direction of the change interrelationship. These change impact metrics are then used to evaluate the overall implementation risk. For most engineering projects, the focus of risk analysis is on the feasibility and viability of the product design and its development process [97]. In terms of change implementation planning, this risk can be divided into cost and process difficulty to execute the required modification. This notion is supported by Huang et al., who stated that the competitive measures for an engineering change process can be based on number of changes, duration of its handling time and amount of cost or efforts that it requires [167]. Naturally, a difficult design alteration also means a higher cost and longer development time. A good reference standard that has been well-recognized is required to be the basis for the qualitative valuation of this impact measure.

Based on the study sponsored by General Accounting Office of the United States, the state of required technology that enables the product to be in the intended size, weight and configuration is perceived as a key factor for a successful product development [139, 329]. In this perspective, a low technology maturity implies that more time and money are required to adequately prepare it for product use [329]. Several available measures of technology maturity for equipments or systems have been developed for military application and among them are Technology Readiness Level (TRL) and System Readiness Level (SRL) [161].

Technology readiness level (TRL) is a formal basis used for technology evaluation that is pioneered by National Aeronautics and Space Administration (NASA) in the early 1990's [329]. According to DoD 5000.2-R, this scheme is appropriate for both hardware and software use [18, 329], and it is described in Table 51.

Table 51: NASA Technology Readiness Level [279]

TRL	Definition
9	Actual system proven through successful mission operations
8	Actual system completed and qualified through test and demonstration
7	System prototype demonstration in relevant environment
6	System/subsystem model or prototype demonstration in relevant environment
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experiment critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

However, it has been argued that TRL is not truly representative of the system readiness for industrial application [279, 300, 329]. While the technology and product development processes are usually parallel to each other, their paths are not integrated as demonstrated in Figure 57. TRL mostly covers “technology risk”, which is related to the probability that the required technology to achieve target product capabilities will not mature within the expected timeframe [299]. In product development process, it is more relevant to study “technical risk”, which captures the likelihood that the product will fail to reach its target requirements due to the risks imposed by present state of the technology in terms of its specific integration into the product system [279].

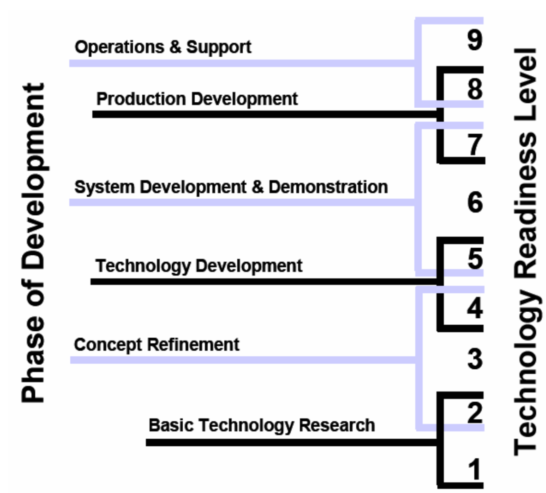


Figure 57: System Development and TRL [279]

Defense Science and Technology Organization within Australian Department of Defense use SRL index to assess "technical risk", which is detailed in Table 52. This SRL index is perceived to be more appropriate than TRL to assess redesign plan because it relates to the system readiness to be incorporated into the product rather than just the general state of its technological development [245].

Table 52: System Readiness Level [23, 279]

SRL	Name	Definition
5	Operations & Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life
4	Production & Development	Achieve operational capability that satisfies mission needs
3	System Development & Demonstration	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility, ensure affordability and protection of critical program information; demonstrate system integration; interoperability, safety and utility
2	Technology Development	Reduce technology risks and determine appropriate set of technologies to integrate into a full system
1	Concept Refinement	Refine initial concept. Develop system/technology development strategy

Based on this SRL index, a qualitative change risk rating scale that is independent of the past change cases and is more reflective of the present modification process is proposed for the SPEC method. This modified SRL scale is given in Table 53.

Table 53: Change Impact Rating Scale

Impact Level	Definition
10	The required component modification is at SRL 1
8	The required component modification is at SRL 2
6	The required component modification is at SRL 3
4	The required component modification is at SRL 4
1	The required component modification is at SRL 5

It can be noted that the modified SRL scale only covers process difficulty associated with the proposed changes. However, it is intuitive that one product component can have a different cost with respect to the others and therefore, even when two components have a similar level of change impact, their incurred costs can be significantly different. This is an essential criterion to be accounted while comparing different change plans. To consider this situation, impact rating for each change effect should also be accompanied by a cost rating. A simple qualitative change cost scale is proposed for this purpose and it is defined in Table 54.

Table 54: Change Cost Rating Scale

Cost Level	Definition
1	Very Low Cost
4	Low Cost
6	Medium Cost
8	High Cost
10	Very High Cost

3.5.2 Taxonomy for Change Propagation Prediction

In addition to change impact risks, there is also a need for a standard guideline in the prediction of change propagation paths. This is closely related to the identification of the underlying change interrelationships between different parts of the product, which often of different types and strength [257]. Nevertheless, not all information about the product is required for change propagation analysis [174]. To have a manageable model size, it is essential to select the right set of information based on the requirements of the analysis tasks in hand. In the application scope of SPEC method, the main analysis requirement is to accurately and efficiently track possible change propagation paths between the product components. Rouibah and Caskey stated that it is easier to assess engineering changes from the product viewpoint because designers perceive the change process as a decision procedure to alter its component parameters [270]. This is supported by Flanagan et al., who stated that designers tasks are often expressed in terms of the parameters [133].

However, the derivation of very detail component attributes demands a tedious modeling effort. It is believed that the routine can be simplified without losing its credibility by using an appropriate taxonomy that can categorize the attributes into their general types of links. In view of this, Pimmler and Eppinger proposed taxonomy for design elements interaction that is described in Table 55.

Table 55: Taxonomy of System Element Interactions [257, 293]

Type of Links	Description
Spatial	The needs for physical space and alignment and adjacency or orientation between two elements
Energy	The needs for energy transfer or exchange between two elements
Information	The needs for information or signal exchange between two elements
Material	The needs for material exchange between two elements

On the whole, this taxonomy considers both fundamental and incidental interactions between the components. The fundamental interactions are the functional relationships that can be in the form of energy, material and signal interchange [126]. Conversely, the incidental interactions are those that result from the translation of the functions into their physical realization [126]. In view of this, the scheme adequately captures all links that exist between two product components as it takes into account both their functional and physical aspects. Moreover, any factors that could affect the change propagation can be easily classified into one of these four categories. By only considering this link definition, the model size is controlled from growing too large while still having adequate details for change process analysis.

Nonetheless, recognizing the type of component interrelationship is only half of the work in predicting change propagation. The possibility of change propagation also depends on in-built design tolerances of the components [142]. For instance, a small level of change effects can be “absorbed” by the component without requiring any modification if they fall within its design tolerance. To account for this condition, the inclusion of change tolerance scale (i.e. high (H), medium (M) and low (L)) for each change relationship is proposed.

3.6 Chapter Summary

Relevance of the proposed SPEC method in the current product development process is further validated and supported from the findings of this literature review. According to Advance Manufacturing Research Newsletter, many product manufacturing companies still typically take weeks or months to get their new product changes into production and the subsequent delays mean financial losses that can exceed the allocated budget [264]. In addition, there have been many redesign cases with a seemingly innocuous change that suddenly blossomed into a series of costly impacts. All these signify the urgent need for a better product redesign planning. Although there is an increasing level of interest in the field of study for engineering change, very few research efforts directly address the issue of change management in product redesign development [117]. In spite of the substantial increase in research activities, the field is still academically under-developed with many researches are individually pursued and fragmented without proper collaboration to each other [174].

The focus of literature study presented in this chapter is based on the identified key areas for the proposed SPEC methodology: baseline assessment, change propagation modeling, change impact analysis and change implementation planning. The methods and tools that have been discussed throughout this review are listed again in Table 56.

Table 56: Tools and Methods in Literature Review

Research Areas	Identified Tools and Methods				
	1	2	3	4	5
Baseline Assessment	Quantitative System Evolvability	System Adaptability Factor (SAF)	Method for Assessing the Adaptability of Product (MAAP)		
Change Propagation Modeling	Functional Change Modeling	Component-Function Propagation Model	Component Linkage Model	Change Favorable Representation (C-FAR)	Product Dependency Model
Change Impact Analysis	Change Propagation Analysis	Progressive Probabilities of Changes	Response Surface Method (RSM) in Change Impact Assessment		
Change Implementation Planning	Redesign-IT	KRITIK	Change Prediction Method (CPM)		

LEGEND: [green] Considered the best per research area

All of them have been qualitatively compared with the required characteristics for use in the proposed methodology, which are outlined based on the identified gaps in aircraft redesign process in Chapter 2 and the research objectives in Chapter 1. Although none of them entirely matches the desired characteristics for their respective area of application, there exists a big potential when their best elements are combined. The perceptively best method for each research area according to the qualitative assessment is highlighted in Table 56 and they are used as the basic building blocks for the proposed SPEC method. This is discussed in following chapter.

Furthermore, based on the general deficiencies that have been identified in the qualitative measurement of change impact, an impact scale rating based on SRL and a simple cost rating have been proposed. Similarly, for the prediction of change propagation path, the taxonomy of system element interactions by Pimmler and Eppinger is suggested for use along with a simple rating for the component change tolerance level.

Using the knowledge gained from this literature review, several research hypotheses are formulated to address the research questions in Chapter 2. These hypotheses, which later become the main basis in the formulation of the proposed SPEC method, are discussed in next chapter.

CHAPTER 4

RESEARCH HYPOTHESES AND PROPOSED METHODOLOGY

"*…engineering change is not the problem. How we handle change, our change proficiency behavior, is the problem*."

- Ring and Fricke (1998)

Based on the literature study presented in preceding chapters, it can be concluded that no known approach that completely addresses identified gaps in the scope of this research is currently available. The review also highlights the urgent needs and potential competitive benefits for aircraft manufacturers to resolve these redesign process deficiencies. Several promising methods and tools for each area of the proposed method have been identified in Chapter 3. The knowledge from the assessment of these methods and tools is valuable in the formulation of research hypotheses for this thesis study.

The first portion of this chapter is allocated to the formulation of the research hypotheses. Based on information obtained from the literature review, these hypotheses are derived to answer the research questions that have been outlined in Chapter 2. For remaining part of this chapter, a detailed explanation of the proposed SPEC methodology is presented. As concluded at the end of Chapter 3, some of the identified methods and tools can either be adapted or combined to create the approaches for each step of the proposed method. A supplementary computer-based support tool is developed to aid in the demonstration of this method. Towards the conclusion of this chapter, the proposed SPEC methodology is compared to the methods and tools that are referenced for its step formulation.

4.1 Research Questions and Hypotheses

Recall the constructed relationships between observations in aerospace industry, research questions and formulated steps of the proposed SPEC methodology in Chapter 2. This is reproduced here in Figure 58.

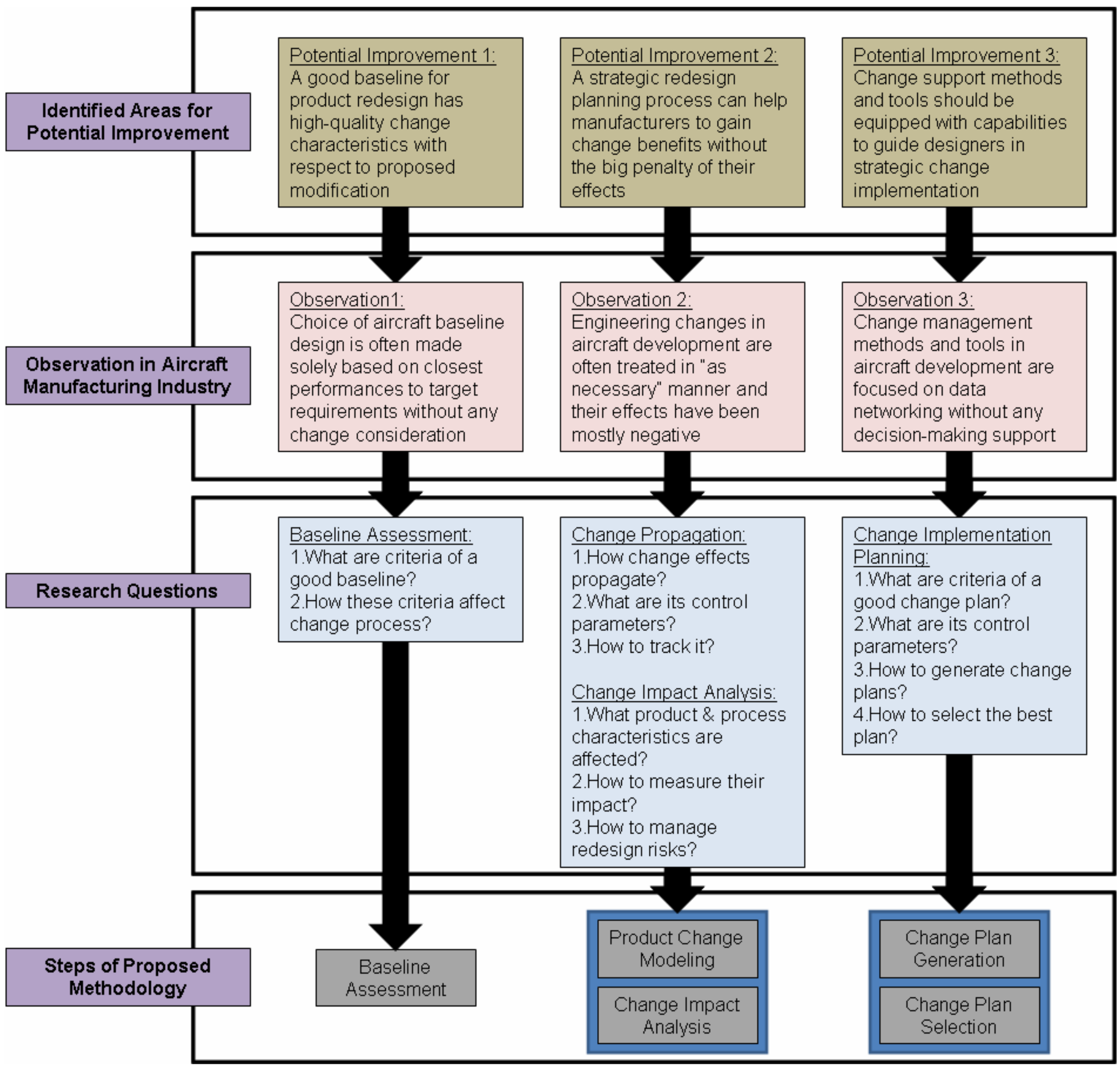


Figure 58: Observations, Research Questions and Proposed Method

Product redesign and change management processes start off with a well-defined baseline [256]. Since the degree of freedom in planning for the required change implementation is dictated and constrained by the existing baseline architecture [326], the redesign process has to be managed around its current design flexibility. The chosen baseline design will govern the change solution space to satisfy the new requirements. It should be mentioned again that apart from the existing aircraft in the market, a baseline within the context of this thesis study also includes conceptual aircraft designs that require modification before making it to the production floor [321]. Based on this apprehension, the first two research questions are outlined as follow.

Research Question 1 (RQ1): What are characteristics of a good baseline for aircraft redesign approach?

Research Question 2 (RQ2): How will these characteristics affect the change process?

The goal of the first research question is to identify aircraft design characteristics that can restrict its flexibility for the change implementation process. In conjunction with that, the second research question addresses how these characteristics govern the possible redesign plans for the required modification. Most baselines are chosen based on their proximity to the target requirements but it is argued that their architectural characteristics also have a big impact on the success of the redesign development. In section 3.1, several standard definitions for product's capability to evolve from its current form have been discussed. It can be implied from reference literatures that depending on product design architecture and driving change requirements, the complexity of the redesign procedure can vary from one product to another. This assertion is formalized by the first hypothesis.

Hypothesis 1 (H1): Aircraft design architecture dictates the complexity of its redesign process.

Each component within the aircraft design has their own functional role in achieving the high-level system performances. If the aircraft performance requirements are modified or newly available technologies are to be incorporated into it, the baseline design has to be changed accordingly. Since each part generally has different manufacturing difficulty, the complexity of the redesign process is greatly influenced by which aircraft components are affected by the proposed changes and the level of impacts imposed on them. Based on this understanding, the baseline suitability for the redesign case is indicated by how well its design architecture can cope with the driving requirements, which is affirmed by this hypothesis 1. In order to prove this notion, redesign process complexity for a few aircraft systems with different architectural designs has to be compared based on the same set of initiating change requirements.

Furthermore, extending from hypothesis 1, the complexity of the redesign process can be strongly associated with the number of affected parts, and the types and levels of change effects that are imposed on them. For the same aircraft, there are different ways that the change requirements can be realized and this condition relates to the change propagation phenomenon. Due to the range of change behaviors that each aircraft part can have, there are some trade-offs while deciding whether the change effects should be transmitted to the next component in the propagation tree or not. This means that the overall change impacts, hence aircraft redesign risks, can be managed by controlling change propagation path. The research questions to address this notion are outlined as follow.

Research Question 3 (RQ3): How engineering change effects propagate from one architecture locality to another?

Research Question 4 (RQ4): What are control parameters of change propagation?

The main objective of the third research question is to recognize the enabling means for change propagation. By knowing how change effects can be transferred from one part to another, the next question is how they can be controlled and this is the goal of the fourth research question. With the understanding on how the change effects can be managed and contained, designers can recognize the existing flexibility that they have while planning for aircraft redesign goals. In current "as necessary" redesign practices, expected change effects propagation is always perceived to be necessary. But as discussed in section 3.4.3, the change roles of each component can vary in different redesign situations and this can lead to different change propagation paths. Each component can have one of the general types of change roles that are described as follow [115]:

- **Absorbers –** propagate no further changes after being changed
- **Carriers –** transferring change to others after being changed but neither reduce nor add to the complexity of the change problem
- **Multipliers –** expand the change problem further by making it more complex
- **Constants –** not affected and not causing changes

It is believed that the paths of change propagation tree can be managed by assigning the aircraft components with their favored change role. This particular notion is emphasized by the second hypothesis.

Hypothesis 2 (H2): Engineering change propagation in aircraft redesign development process can be managed by dictating the change role of its components.

Because each component can introduce different level of change effects, several trade-offs are involved while making the decision to change one component over the others or to impose a higher or lower change level on it instead of the others. If the component poses a high development risk when it is modified and propagates its change effects to other high-risk components, its change role can be designated as a “constant”. In product manufacturing industry, some of these “constants” have been pre-determined before the redesign process is initiated due to company’s policy or business strategy. To corroborate hypothesis 2, potential propagation paths that are constructed by varying the component change role in response to the same initiating changes for the same aircraft design need to be compared.

In conjunction to hypothesis 2, assignment of component change role affects the change propagation tree by varying the measure of its change-related parameters. To accurately predict the change propagation paths, information of these related parameters should be included into the aircraft change model. However, several issues regarding the trade-offs between the level of details for the model and the extent of its modeling effort have been prominently raised in literatures, apart from the model effectiveness to capture the change propagation phenomenon. This matter is the goal for the following research question.

Research Question 5 (RQ5): How to properly model the aircraft system to track the potential change propagation?

This fifth research question aims to outline the required characteristics of aircraft model to enable an accurate prediction of the change effects propagation. Based on the literature review in section 3.2, it has been established that the change effects are transmitted from one component to another according to their type of relationship and their level of design change tolerance. In view of that, if the modification does not affect their functional or physical interrelationship, no effect is propagated from the initiating component to them. Moreover, most components are developed with some degree of design tolerances. If the propagated change effects fall within its design tolerance, the component can absorb them without requiring any modification and this ends the change propagation tree. These situations need to be captured by the model through proper definition of its parameters. To control the complexity of aircraft change model without reducing its competency to predict the potential change effects propagation paths, a standard modeling guideline is necessary. Rationally, a parameter can be explicitly defined for the change tolerance level of each aircraft component but the same cannot be applied to capture the essences of the change propagation. An appropriate taxonomy for existing interconnections is required to enable correct prediction of the propagation tree. This notion is reflected in the following third hypothesis.

Hypothesis 3 (H3): Potential change propagation tree within an aircraft design can be predicted by using the taxonomy of system element interactions and the level of its component's change tolerance.

In section 3.5.2, the taxonomy of system element interactions proposed by Pimmler and Eppinger is considered to be the best reference that captures the prediction of the change propagation due to the type of the component interconnections. Its application with the change tolerance level is perceived as the best foundation in balancing the details and the modeling efforts for the aircraft change model. Although many existing change modeling techniques recognize the needs to categorize the types of interrelationships, they do not formally employ a standard taxonomy. This leads to much unnecessary information being included into the model and wasting valuable modeling and computational efforts. On the other hand, while there are also methods that apply this particular taxonomy of system element interactions or the change tolerance parameter separately, no reference is found in the literature that formally utilized both of them together for the aircraft change model. To prove hypothesis 3, this scheme needs to be applied in an aircraft redesign problem to demonstrate its structured modeling approach for a manageable model complexity and its capability to predict change effects propagation. A comparison with other modeling techniques can also be done to further supplement this assertion.

Using both hypotheses 2 and 3, alternative change propagation paths can be mapped out and their corresponding set of affected components can be identified. The next step is to evaluate the development risks for these different redesign plans. The following research questions are outlined to gather the necessary change information and to find the best approach to assess the level of change risks.

Research Question 6 (RQ6): What are characteristics of an aircraft and its development process that can be affected by engineering changes?

Research Question 7 (RQ7): How to sufficiently measure change impacts on these characteristics?

Research Question 8 (RQ8): How to manage overall aircraft redesign risks?

At this point of discussion, it can be inferred that the effects of engineering changes will not only affect the aircraft architecture but also its development process characteristics. It is imperative for designers to be able to distinguish all redesign trade-offs during their decision-making process, especially those with regards to the negative change effects. In view of that, the sixth research question is focused on identifying the aspects of aircraft design and its development process that can be affected by engineering changes. Once they are identified, the seventh research question addresses how they can be appropriately evaluated to accurately reflect on their level of intensity and urgency during the decision-making process. Their combined effects indicate the overall redesign risks for the change plan. In section 2.1.1, the utmost value for manufacturers to consider redesign approach is the capability to produce derivative aircraft that can satisfy the new requirements with a cheaper and shorter development process than it will take them to produce new original aircraft. Though this can lead to sub-optimal derivative designs, most redesign decisions are often tailored to the estimated risks based on redesign development costs and amount of reworks involved [116]. The eighth research question is designated to resolve how the overall risks for the change plan can be managed accordingly. Due to emphasis of change effects on costs and amount of reworks, redesign risks can be associated with the affected components and the cumulative handling time, cost and efforts required for their entailed modification [167]. These factors have been linked to the change propagation path and it can be implied that the level of redesign risks can be managed through proper planning of the change propagation tree. This impression is avowed by the following hypothesis.

Hypothesis 4 (H4): Associated risks of aircraft redesign development process can be controlled by managing change propagation paths.

From hypothesis 2, the management of change propagation paths can be accomplished with the assignment of component change role. Based on the decision to either absorb or propagate the changes, the aircraft components will be affected differently. This situation subsequently leads to different cases of development risks. In other words, by choosing whether the component should absorb or propagate the change effects that are imposed on it, designers are effectively managing the risks of aircraft redesign process. To attest this hypothesis 4, redesign risks associated with at least two change effects propagation paths due to the same set of change requirements on the same aircraft design needs to be compared.

In relation to hypothesis 4, apparently there is a big misconception that the redesign plan with the smallest number of affected components always corresponds to the lowest development risks [344]. For instance, the computer-based change tool by Lin et al. aims to modify a product design to meet its new requirements with minimum changes [202]. However, based on hypotheses 2 and 4, this perception is rather misleading and this view is further emphasized by the following hypothesis 5.

Hypothesis 5 (H5): Aircraft redesign plan with minimum number of modified components does not automatically mean minimum development risks.

The proof for hypothesis 5 can be accomplished in combination with that of hypothesis 4. In this case, the risks for different redesign plans can be compared with the number of components that are affected by them.

Last but not the least, the main objective for the proposed redesign method is to generate and select the best aircraft redesign plan in response to the driving change requirements. As the ultimate tie-in for previous hypotheses and research questions, there needs to be an appropriate procedure on how the knowledge obtained so far can be used to generate and select the best aircraft redesign plan. This is the objective for the following research questions.

Research Question 9 (RQ9): What are important criteria for a good change implementation plan?

Research Question 10 (RQ10): What are control parameters that are available in change planning?

Research Question 11 (RQ11): How to generate implementation plan for the required changes?

Research Question 12 (RQ12): How to select the best change implementation plan among the possible alternatives?

Research question 9 is aimed at extracting the important criteria of the aircraft and its development process that ought to be considered during its redesign planning. In general, the essences of redesign risks can be broken into the performance and process risks. The performance risks correspond to the possibility that the aircraft modifications will fail to satisfy the performance constraints while the process risks cover the likelihood of failure to execute the aircraft redesign process within the development constraints. These risks can be used as an indicator for the goodness of the redesign plan. By knowing important metrics to compare different change plans, the next thing is to identify the change process parameters that enable designers to manage them. This is addressed by research question 10. These parameters later become the primary means to generate the redesign plans and their proper use for this purpose is explored through research question 11. Subsequently, research question 12 seeks the best approach to select the best among the generated plans.

Redesign risks are closely linked to the change effects and following hypothesis 4, the implementation plans are derived by managing their paths of change effects propagation. In addition, there are commonly several initiating changes that have to be handled in the beginning of the redesign process. Most methods or tools found in reference literatures plan for the changes separately. However, it is acknowledged that their effects can be interrelated when these independently planned change propagation paths affect the same components [120, 272, 332]. This leads to the notion that lower redesign risks could be obtained if the implementation of all initiating changes is planned concurrently, which is affirmed by following hypothesis.

Hypothesis 6 (H6): Change implementation risks can be minimized by simultaneously planning for all initiating changes in aircraft redesign process.

If the implementation of the initiating changes is independently planned into the aircraft, there are potential redesign conflicts when the same components are affected by several of them. This is mainly due to the fact that the characteristics of those components will be altered for one change plan and their new condition is not considered during the planning for the other initiating changes. Therefore, the estimated risks from this "one-at-a-time" redesign planning approach can be misleading as it does not capture the correct level of effects imposed on the components. In contrast, by simultaneously consider the initiating changes; the redesign planning benefits from the updated components state if they are affected by another initiating change. This condition enables a better estimation of the overall redesign risks and helps in making better redesign decisions regarding the change propagation paths. To prove hypothesis 6, redesign risks for the change plan that is derived by 'one-at-a-time' approach needs to be compared with that developed through simultaneous consideration of the initiating changes.

To summarize, the flow of research questions and hypotheses for this thesis study is illustrated in Figure 59.

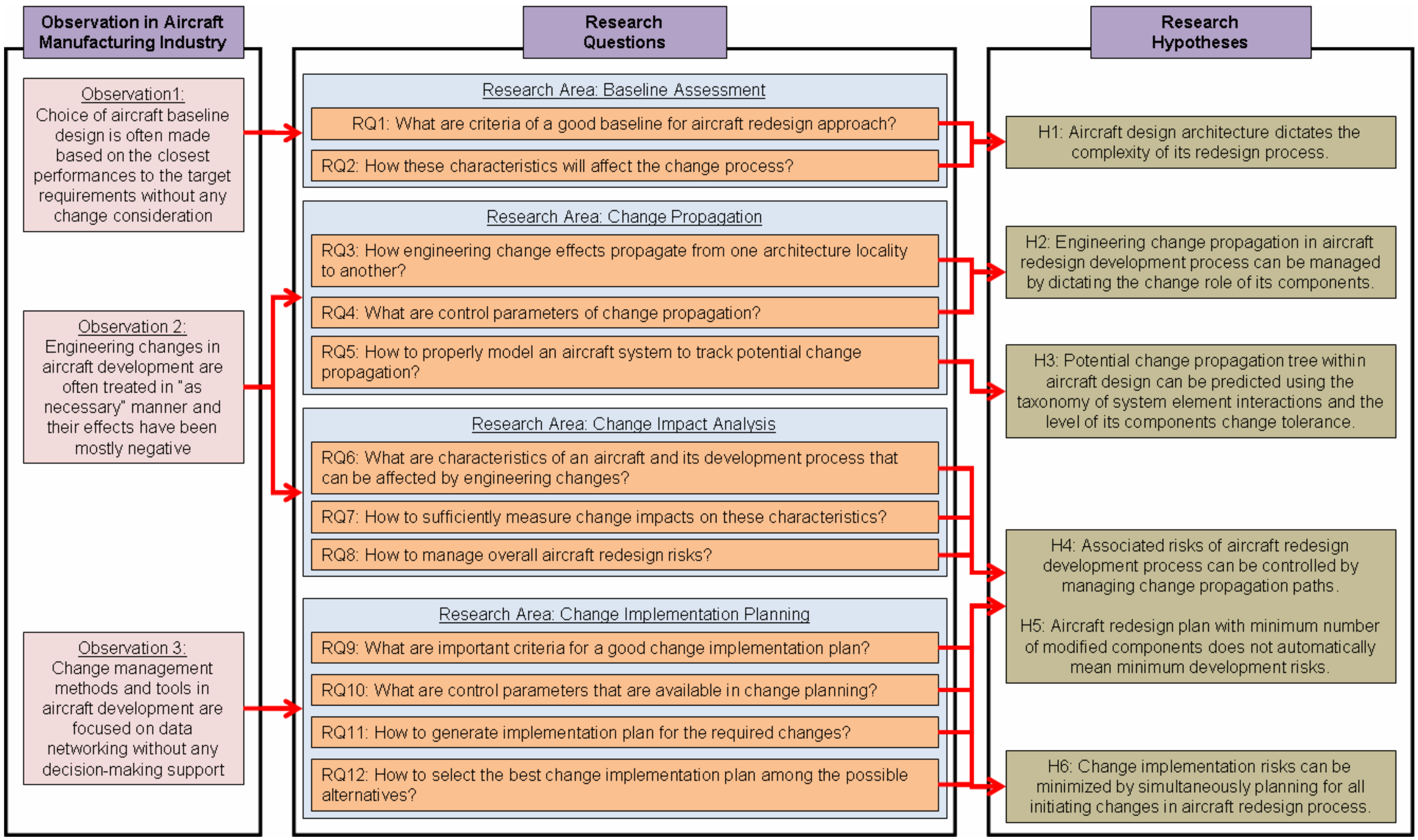


Figure 59: Summary of Research Questions and Hypotheses

4.2 Proposed Methodology

Recall the initial formulation of the proposed SPEC method, which has been constructed based on the assessment results of six available product redesign and change management frameworks in Chapter 2. From the same assessment process, several gaps to the required characteristics of the proposed method have been identified and this knowledge is used to drive the scope of literature review study in preceding Chapter 3. Several methods and tools that are presently available are identified and compared to the required criteria for the proposed methodology, and they become the main basis in bridging the identified gaps in this research study.

The objective of this section is to apply the knowledge gained from the literature study in formulating the steps for the proposed SPEC methodology. In addition, an accompanying computer-based tool to support its implementation is developed and this prototype Excel-based tool is discussed through a simple demonstration case of electrical power system. The sequence of steps for the proposed SPEC methodology has been outlined in Chapter 2 and is reproduced here in Figure 60. Each of its steps is detailed in this section.

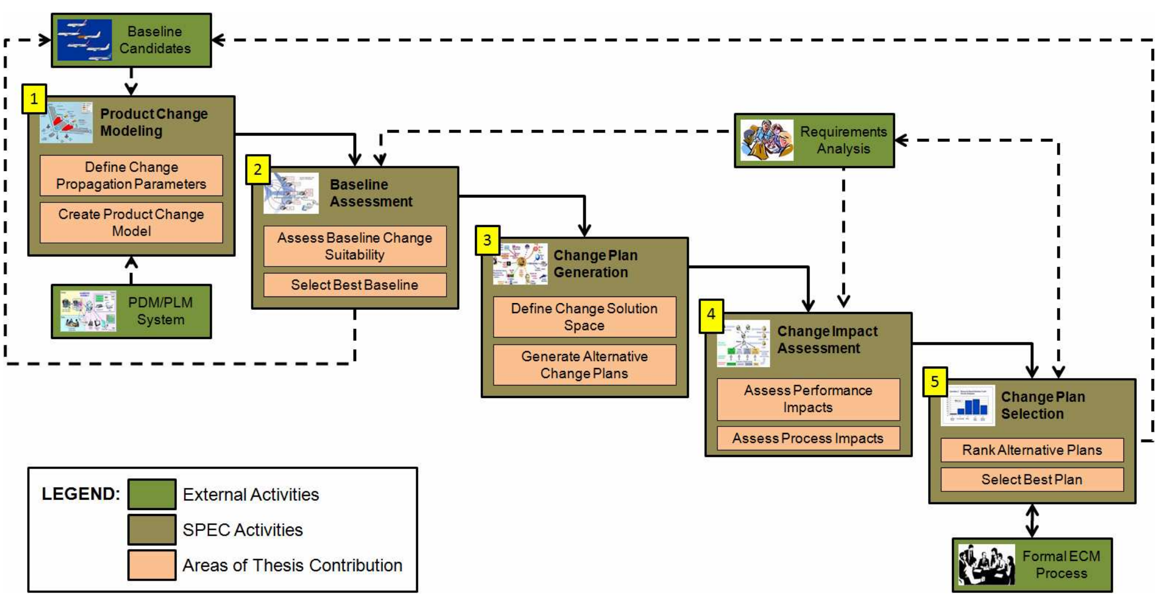


Figure 60: Proposed Framework for SPEC Methodology

As mentioned, a complementary Excel-based aircraft redesign support tool is developed to facilitate the demonstration of the proposed SPEC method. The snapshot of the main program interface of this support tool is depicted in Figure 61. Intuitively, each step in the proposed SPEC methodology corresponds to an individual step in this tool.

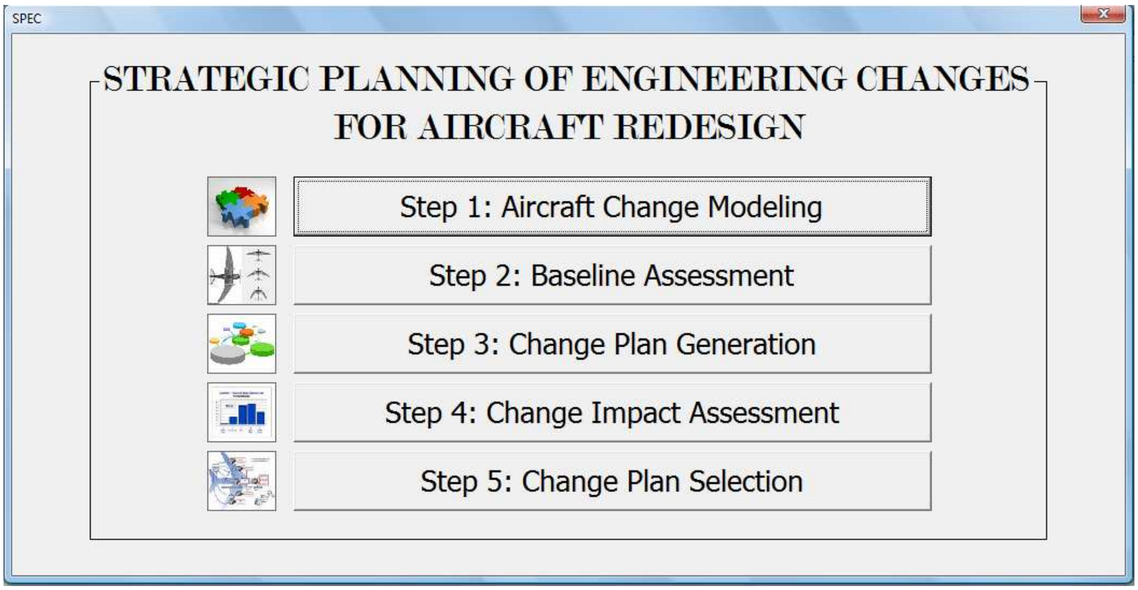


Figure 61: SPEC Support Tool Main Program Interface

4.2.1 Step 1: Aircraft Change Modeling

The objective of Step 1 is to produce a well-balanced aircraft change model for predicting change effects propagation and analyzing change impacts to support the decision-making process during change implementation planning. From literature study in section 3.2, the problems with available change modeling methods have been discussed. Subsequently, they characterize the challenges in developing the aircraft change model for the proposed SPEC method. Based on previous reviews, it has been established that the construction of a good change model must include following considerations:

- A functional or physical interconnection between two components does not automatically mean that they are change-related to each other

- A change interrelationship between two components does not always work in both directions
- Change effects are propagated only when the type of changes made in the initiating component matches the type of links it has with the other component
- A change that is imposed on one attribute of the component might also affect its own other attributes

The aircraft change modeling procedure for this Step 1 takes into account all these points. It is prominently based on Product Dependency Model (detailed in section 3.2.5), which has been assessed as the best product system change model from the literature review.

Firstly, DSM representation has been chosen for the aircraft change model. This decision is based on its highly advertised efficiency and versatility in aiding the analysis of inter-relationships between product elements. As concluded in section 3.2.6, DSM is possibly the best model representation for product engineering change study at the moment [293].

Secondly, change modeling process can be approached either from functional or physical aspects of the aircraft design, which are complementary to each other. It has been argued that one of the main emphases in aircraft redesign planning is to establish the degree of flexibility for the baseline design since change implementation process is significantly constrained by its existing architecture. In section 3.2.3, Jarratt suggested that the most suitable approach to properly capture existing design change constraints is by identifying physical components in the product architecture and observing how they are interrelated to one another [174]. The understanding of these interrelationships influences the ability and efficiency of manufacturers to undertake and manage the modification made on their product, particularly in predicting potential change effects propagation [81]. In section 3.5.2, it has been discussed that the prediction of change effects propagation can be effectively made by modeling the aircraft using taxonomy of system element interactions by Pimmler and Eppinger [257] and with supplementary information of its component change tolerance level.

Considering these arguments, construction of the aircraft change model is approached from its physical system decomposition and the interrelationships that exist between its components are identified based on the taxonomy of system elements interactions that is reproduced in Table 57. In addition, information regarding the change tolerance level for each component is also included in the aircraft change model and this is defined in Table 58, which is loosely based on Product Dependency Model scheme.

Table 57: Taxonomy of System Element Interactions [257, 293]

Type of Links	Description
Spatial	The needs for physical space and alignment and adjacency or orientation between two elements
Energy	The needs for energy transfer or exchange between two elements
Information	The needs for information or signal exchange between two elements
Material	The needs for material exchange between two elements

Table 58: Change Tolerance Level Definition

Type of Information	Definition Scale	Description
Attribute Change Direction	Increase	The increment in the related attribute level
	Decrease	The reduction in the related attribute level
	Either Way	Both increment and reduction in the related attribute level
Tolerance Level	None	Have no tolerance and always be modified if the change effects are propagated
	Low	Can tolerate low level of propagated change effects without requiring any modification to itself
	Medium	Can tolerate medium level of propagated change effects without requiring any modification to itself
	High	Can tolerate high level of propagated change effects without requiring any modification to itself

According to Pimmler and Eppinger, it is suggested that the details of the system model is at least a level down than that required for its subsequent analysis study [257]. From observation made on past aircraft derivative initiatives, most aircraft design variants were derived through incremental subsystems development. Based on this notation, the aircraft change model needs to at least capture the major components of its subsystems. This is to ensure that sufficient information is available and basis for impending change analysis is appropriately covered.

Moreover, in order for the proposed SPEC methodology to be in line with real industrial practices, physical decomposition of the aircraft system is tailored to the standard ATA Specification 100 (ATA-100). ATA-100 is introduced by Air Transportation Association of America (ATA) as a guideline for aircraft service and maintenance documentation. It covers various types of air transportation vehicle such as turbofan-powered and propeller-driven aircraft, with each chapter corresponds to a specific subsystem. Due to its wide coverage of different air vehicle types, not all ATA-100 chapters are always applicable for the task at hand. The focus in this research study is on commercial transport aircraft type and in view of this, ATA chapters 46 and 47 for instances can be excluded because they respectively correspond to the armament and weapons electronics.

A complete ATA-100 breakdown is available on ATA official website [2]. ATA chapters included for aircraft change model in the proposed SPEC method are depicted in Figure 62, which is taken from the program snapshot of the developed SPEC tool. It should be noted that Federal Aviation Administration (FAA) has produced their version of ATA-100, which is known as Joint Aircraft System/Component (JASC) [8]. Both standards are very much similar to each other but JASC provides more information concerning details of the subsystem breakdown process. Therefore, while ATA-100 is the main reference in outlining the breakdown procedure, JASC is used as its complementary reference.

Figure 62: Considered ATA-100 Chapters for Aircraft Change Model

On the whole, the sequence of phases for this first step of the proposed SPEC method is presented in Figure 63. This step begins with the physical decomposition of the candidate baseline aircraft. It is assumed that these baseline candidates have been identified prior to the initiation of this step and their available data in the company's PDM or PLM systems can be used accordingly for this modeling process. The identified major components for each aircraft subsystem are represented in the DSM model, which is then populated with their existing design interconnections that are identified based on the taxonomy of system elements interaction. Each of these links is also furnished with the information regarding their change tolerance level. In the end, the main output from this Step 1 is the completed aircraft change interrelationship matrix (CIM).

To demonstrate the execution of this Step 1, consider the modeling example of electrical power subsystem onboard Boeing B737-200 aircraft design. In reference to its schematic presented in [180], the simplified block diagram that highlights its major components is depicted in Figure 64.

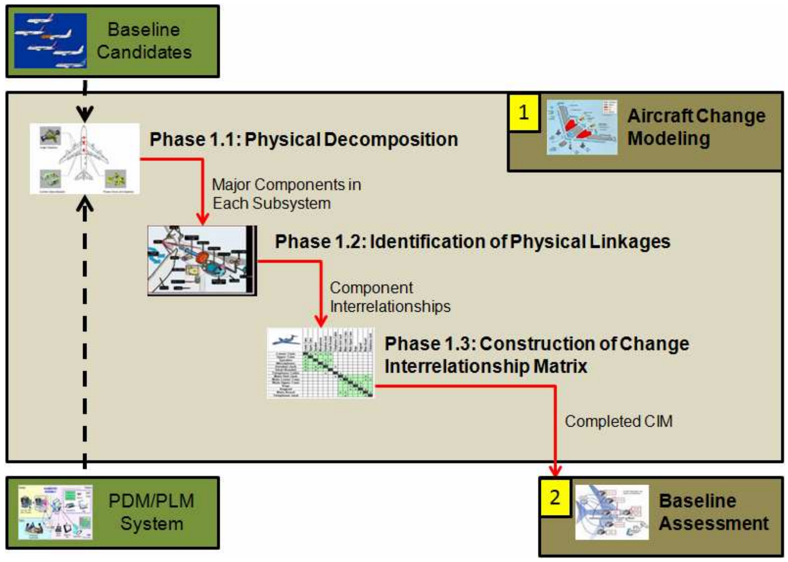


Figure 63: Overall Workflow for Step 1

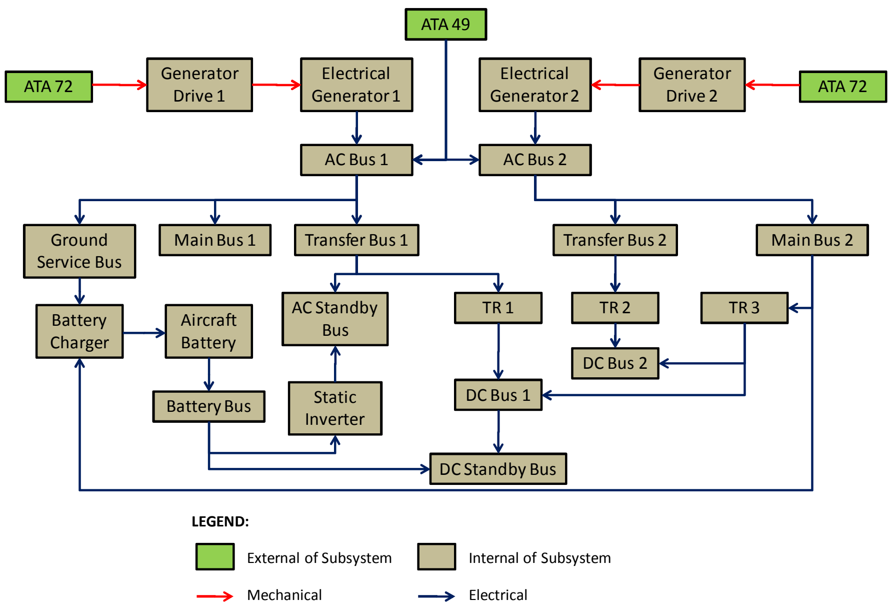


Figure 64: Block Diagram Representation of B737-200 Electrical Power Subsystem

Referring back to Figure 63, the subsequent step after the physical decomposition process is to list the identified major components into DSM format. Once this task is completed, their intra-relationships are identified in accordance to the taxonomy of system elements interaction and assigned with respective change tolerance level. Interrelationship between the components of different subsystems is then identified in similar manner and ideally, this is done once all aircraft subsystems have been modeled internally. This is to ensure consistency of the aircraft change model where any discrepancies that exist can be easily noted when connecting components for any expected interrelationships are missing from the aircraft change model. The resultant change model for the electrical power subsystem is shown in Figure 65. To conclude, summary of this step-by-step procedure is depicted in Figure 66.

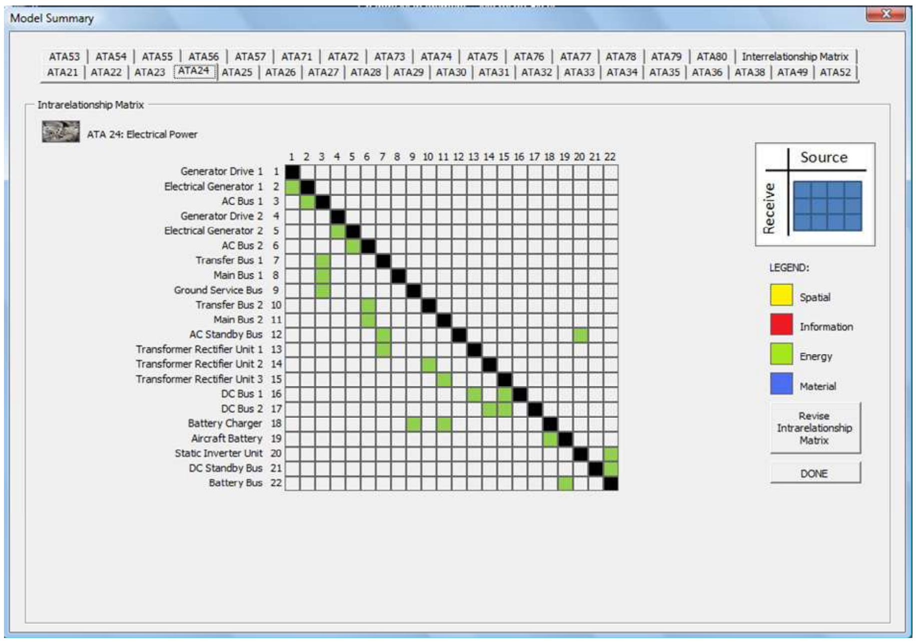


Figure 65: Sample Change Model for B737-200 Electrical Power Subsystem

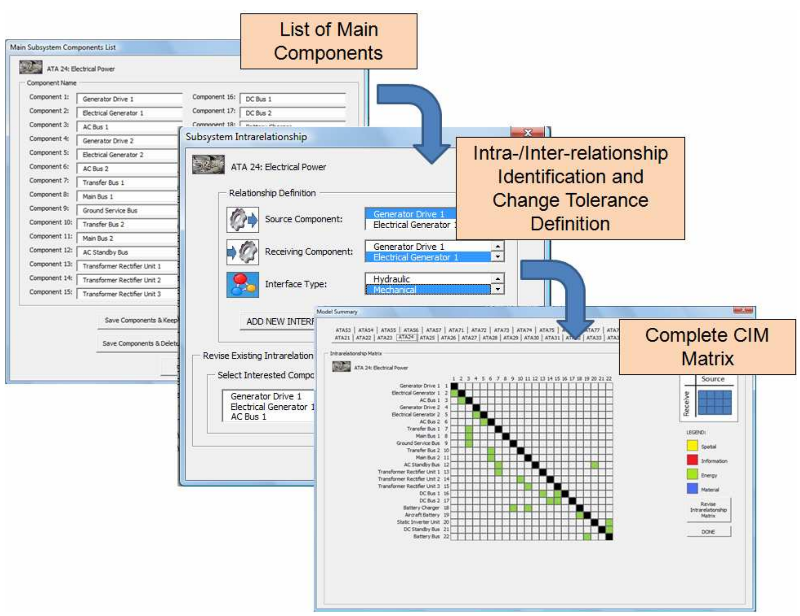


Figure 66: Aircraft Change Modeling by SPEC Support Tool

4.2.2 Step 2: Baseline Assessment

With the aircraft change model already constructed in Step 1, primary goal of this second step in the proposed SPEC method is to evaluate the selected baseline aircraft suitability to undergo its redesign changes. In cases when there is more than one baseline candidate, this step becomes the process to select the most appropriate baseline aircraft with regards to the driving change requirements.

In previous literature study, several definitions and related metrics regarding product design adaptability characteristics have been identified. Despite their different terms, they essentially share similar basis and are easily related to each other. For the proposed SPEC method, the main emphasis is on the planning of engineering change implementation. In view of this, the focus of baseline aircraft assessment process should consider the existing design architecture since it is known to dictate the available degree of design flexibility for the proposed modification. From the perspective of product system design, potential change impacts are closely related to its complexity, architecture build-ups and degree of innovation [174]. The complexity over product design generations can be measured by the number of decomposed elements and the connectivity between them [127, 179, 313]. In theory, a product is more difficult to be redesigned when its parts to be modified are highly dependent on its other parts [221]. Nevertheless, it should be realized that the most evolvable design candidate is not always the best option for the change implementation task at hand because it is possible that the process can still be too costly or risky [75]. Hence apart from the usual baseline selection based on the proximity of its performances to the driving requirements, development risks should also be an evaluation criterion to select the right baseline design. Overall, the preferred redesign plan is concluded to be the one that involves a small number of parts, requires less new parts and interrelationships, and can be accomplished with a low risk and cost [138]. All these characteristics have to be measured in the baseline candidate.

Based on above arguments and the conclusions made from the assessment of methods in section 3.1.4, evaluation metrics from quantitative system evolvability method are taken to be reference measures for the baseline aircraft assessment with regards to the proposed redesign changes. However, their definition has to be slightly adjusted to match the scope of product redesign process instead of new product development that they are originally developed for. The modified definition for the metrics is tabulated in Table 59.

Table 59: Modified Aircraft System Evolvability Metrics

Evolvability Metric	Description
Generality	The capacity of the aircraft system to accommodate the changed or new requirements without requiring any changes to its design
Scalability	The capacity of the aircraft system to accommodate the required change by the scaling of its existing design without requiring any new components
Adaptability	The capacity of the aircraft system to accommodate the required change without propagating the change effects beyond the initiating components
Extensibility	The capacity of the aircraft system to accommodate the required change with the effects propagation allowed
Complexity	The capacity of the aircraft system to accommodate the required change without increasing its design complexity level

In addition, recall that it is favorable to have minimum affected parts and interfaces, and it is also essential to evaluate whether the derivative aircraft will maintain the same level of design flexibility as its baseline. In general, a less complex system design minimizes the risks of propagated change effects because its components or parts are not intricately interlinked to each other. Plus, if the baseline design is theoretically flexible, changeable and enhanceable, its complexity will not markedly increase after it has been modified. In section 3.1.3, this aspect of product adaptability is stressed by MAAP through its "parts" and "connectors" metrics. Since derivative development approach is dominant in aircraft industry, it is essential for the derivatives to have only a little change in complexity to allow further incremental development. To account for this condition, system complexity criterion is added into the evolvability metrics for this SPEC method.

As discussed in section 3.1.1, quantitative system evolvability method does not provide a structured approach on how these assessment metrics should be measured apart from its proposed DSEA rating scale. Unfortunately, this scale is focused on high-level system change assessment and does not directly consider the specific state of baseline design architecture. In section 3.1.4, it has been concluded that MAAP is equipped with the best evaluation scheme that is more transparent for its adaptability metrics. The adaptability criteria used in MAAP can be easily associated with aircraft system evolvability metrics defined in Table 59. Based on this, several measurement procedures in MAAP are used as the reference to derive proper evaluation scheme for the aircraft system evolvability metrics.

For generality criterion, there are only two possibilities: whether the requirements can be satisfied without requiring any changes on the existing aircraft system architecture or not. A rating of 0 is given in the former condition while the latter case corresponds to a rating of 100. This rating assessment is done for each requirement and their total becomes the overall generality risk measure. Similarly, there are only two possibilities for scalability metric. The baseline aircraft needs to be assessed whether it can meet the requirements through the scaling of its existing design without requiring additional new components and interfaces or not. Accordingly, a rating of 0 is given in the former scenario to indicate a low risk level while the latter case corresponds to a penalty rating of 100. This is done for each requirement case separately and their total becomes the overall scalability risk measure.

For adaptability criterion, the baseline aircraft design has to be evaluated in terms of its capability to contain the initiating changes within the directly affected design architecture locality. It should be noted that the proposed initiating changes are assumed to be known prior to the initiation of this step and the evaluation is executed with respect to specific change accommodation tasks from that redesign decision. As established in section 3.5.1, the measures for engineering change process can be based on amount of cost and efforts that it requires, which translates into its risks if the process fail to meet the requirements even after the changes have been made. Based on CPM in section 3.4.3, the risk metric can be evaluated as the product of change likelihood and change impact ratings, which is associated to the scheme that has been widely used in product risk management field [13, 80]. For this proposed SPEC method, the focus is on assessment of the different potential change plans. If a component is considered for modification, then its change likelihood is 1. Accordingly, its probability is 0 if it is not included in the change plan. On the other hand, the change impact in this proposed method is measured from two primary aspects of redesign process that have been established from literature study: expected cost and process difficulty to execute the redesign development. In view of this, the adaptability risk is measured by Equation 14 and is evaluated for each individual change requirement. Note that if the adaptability is not possible, the highest penalty score of 100 is assigned.

$$Adaptability\ Risk = \begin{cases} \left[Cost_i \times Impact\ Level_i\right]_{without\ propagation} & if\ \ possible \\ 100 \quad if\ \ not\ \ possible \end{cases} \qquad \text{Equation 14}$$

where $Cost_i$ = change cost metric for initiating component *i*

$Impact\ Level_i$ = change impact level metric for initiating component *i*

In contrast to adaptability criterion, the change effects are allowed to propagate from the initiating components to other parts of the baseline aircraft architecture during assessment for its extensibility characteristic. With the same arguments that have been presented for the calculation of adaptability score, the mathematical equation for extensibility risk is given by Equation 15 and is separately calculated for each change requirement case.

$$Extensibility\ Risk = \begin{cases} [Cost_i \times Impact\ Level_i]_{with\ propagation} & if\ \ possible \\ 100\ \ if\ \ not\ \ possible \end{cases} \qquad \text{Equation 15}$$

where $Cost_i$ = change cost metric for initiating component i

$Impact\ Level_i$ = change impact level metric for initiating component i

Based on the above equations for change adaptability and extensibility characteristics, the cost and impact levels of the required modification on the affected component need to be established for the evaluation. In general, change risk analysis is focused on feasibility and viability of the product design and its development process [97], which is translated into the levels of difficulty and cost to realize the required modification. In section 3.5.1, SRL index (as defined in Table 52) has been recognized as a proper reference for the qualitative change risk rating that is independent of historical change cases while at the same time provides a good reflection of the current change process at hand. All in all, the change impact and qualitative cost rating scales to be applied in this proposed method are presented in Table 60 and Table 61, respectively.

Table 60: Change Impact Rating Scale

Impact Level	Definition
10	The required component modification is at SRL 1
8	The required component modification is at SRL 2
6	The required component modification is at SRL 3
4	The required component modification is at SRL 4
1	The required component modification is at SRL 5

Table 61: Change Cost Rating Scale

Cost Level	Definition
1	Very Low Cost
4	Low Cost
6	Medium Cost
8	High Cost
10	Very High Cost

The above computation for adaptability and extensibility change risks only focuses on the initiating change components and does not include the potential others in overall change propagation tree. The main reason for this is because the complete redesign plan is yet to be determined. Even so, the initiating components are sufficient to derive a conservative estimate of the development risk. If the extensibility risk is calculated to be higher than the adaptability risk, this implies that change effects propagation is not desirable and that measure of adaptability risk is likely to be the best possible level of redesign risk that can be expected for the baseline with respect to the particular change requirement. The level of difference between adaptability and extensibility risks can be perceived as a qualitative measure of possible reduction or increment of the redesign development risks that can be gained by purposely propagating the change effects to other components instead of totally absorbed by the initiating components.

Last but not least, in reference to DFA method, the following equation is used to assess the relative complexity of the modified aircraft design to its baseline.

$$Complexity\ Score = \left(\frac{new\,\#\ of\ \ parts}{existing\,\#\ of\ \ parts} \right) + \left(\frac{new\,\#\ of\ \ int\,errelationships}{existing\,\#\ of\ \ int\,errelationships} \right) \quad \text{Equation 16}$$

The interrelationships refer to connections that exist between the subsystems and within each individual subsystem. As aircraft subsystems are usually developed independently, the design complexity level arises when various subsystems have to be coordinated by their separate manufacturers. The higher the complexity score is; the more complex the levels of the redesigned system design and its development process are expected to be in comparison to its baseline. A highly complex system design is also more susceptible to the high risks of change effects propagation [115]. Using the same reasons as before, this complexity measure for baseline assessment process is also focused only on the proposed changes for the initiating change components.

Finally, the overall measure of baseline aircraft suitability with regards to the change task is defined in the following Equation 17.

$$\textit{Overall Evolvability Risk}, f = \sum w_i x_i \qquad \text{Equation 17}$$

$w_i =$ weighting for evolvability metric i
$x_i =$ normalized risk score of evolvability metric i
i = evolvability metric as tabulated in Table 59

The normalization of risk score for each metric is derived by dividing the computed value with their corresponding worst case scenario. For generality or scalability assessment, the worst case is when all driving change requirements are given a score of 100 that implies they cannot be accomplished with little or no modification of the baseline candidate. On the other hand, for adaptability and extensibility metrics, their worst condition is for each initiating change component to be assigned with a risk score of 100. When more than one baseline candidate are under evaluation, this normalization procedure will involve the worst case scenario among them. By doing this, it gives a meaningful risk comparison between them and properly penalizes the candidate with a higher number of initiating components. Note that from Equation 16, the ideal score for the complexity metric of a single design is taken as 2, which refers to the case where no significant change in the complexity level of the derivative design in relative to its baseline is expected. However, the normalization of this complexity metric is done with reference to the most complex system architecture if more than one candidate is considered. The resultant complexity metric value can thus be interpreted as the relative level of design intricacy between the candidates. After all these assessments have been completed, the baseline candidate with the lowest overall evolvability risk measure can be perceived as the best for the required change tasks at hand. Overall, the sequence of phases for this step in the proposed SPEC method is illustrated in Figure 67.

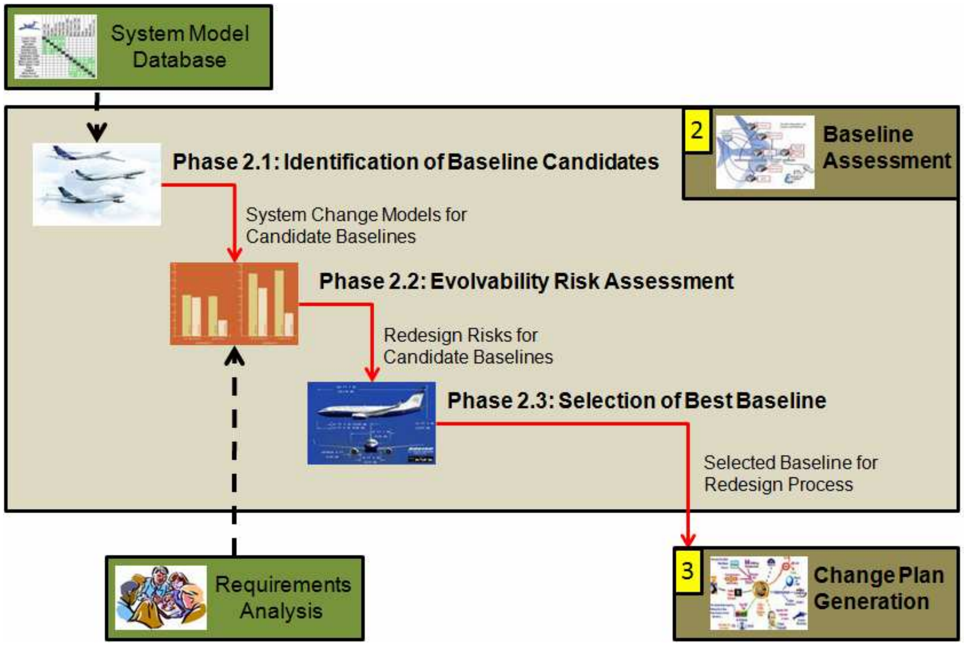


Figure 67: Overall Workflow for Step 2

In brief, the process starts with the identification of baseline aircraft candidates and it is assumed that they have been modeled in preceding Step 1. The requirements analysis is not part of the proposed SPEC method and is presumed to have been done prior to its initiation. Based on the pre-defined change requirements, the baseline aircraft candidates are independently assessed to identify their corresponding initiating change components and to establish the score for their system evolvability metrics. Once this is completed for all baseline candidates, the next phase is to compare them and select the best baseline for the redesign task. During this phase, the evolvability metrics are weighted to reflect their relative importance, which corresponds to manufacturer's preferences in completing their redesign task. If the manufacturer prefers to have minimum affected components and interfaces, a relatively low weighting can be assigned for the extensibility metric. Finally, candidate with the lowest evolvability risk score is taken as the best baseline with regards to the change requirements.

To demonstrate the execution of this Step 2, consider back the previous electrical power subsystem example. Let assume that the driving requirements for its redesign process are as tabulated in Table 62 and Boeing B737-200 has been chosen as one of the interested baseline candidates. For simplicity, this demonstration example is restricted to only the change effects on electrical power subsystem.

Table 62: Example Change Requirements

Change Requirements	Target / Constraint	B737-200 Adv Performance [338]
Performance Requirements 1. Flight Range 2. Gross Weight	 1750 nmi 114,000 lb	 2000 nmi 116,000 lb

Based on information in Table 62, generality and scalability scores for Boeing B737-200 aircraft against the requirements can be made. Because its current flight range capability exceeds that of the driving requirement, it earns a generality risk score of 0. For the same reason, a scalability risk score of 0 is assigned for this requirement. In contrast, since its current gross weight is larger than required, a generality score of 100 is assigned. For the scalability risk score of this requirement, it is predicted that the design could be slightly scaled down to improve on its weight characteristics and thus given a score of 0. Note that each driving requirement is independently assessed. Although it is possible that the scaling of the design architecture for one requirement negatively affects its performance with regards to the other driving requirement, those conflicts can be taken to be resolved by further system modifications that are considered in adaptability and extensibility risks assessment. Overall, the generality and scalability risks scoring process for this example case is summarized in Table 63.

Table 63: Example Calculation of Generality and Scalability Scores

Requirement	Generality Assessment	Scalability Assessment
Flight Range	0	0
Gross Weight	100	0
TOTAL	100	0
"Worst Case Scenario"	2*100 = 200	2*100 = 200
Normalized Score	½ = 0.50	0

While the aircraft design can be sized down to reduce its gross weight, such scaling down process can also affect its range capability with the downsizing of the onboard fuel tanks. To ensure that the penalty does not violate its range requirement, further weight reduction is sought through several other alternative system design changes. From the requirement analysis done prior to the initiation of this method (which is not covered in this proposed method), it is assumed that this issue is decided to be resolved by the implementation of electrical starter-generator. As shown in Figure 64, power generation mechanism in the current electrical power subsystem is accomplished through the use of a generator drive and electrical generator assembly, which can be expensive, heavy and inefficient [260]. The application of an electrical starter-generator technology in its place can improve the overall weight characteristic of the aircraft system, especially with additional elimination of conventional pneumatic air starter unit for the engines. This proposed redesign change to cope with the gross weight requirement will require substitution and elimination of the existing electrical AC generator and its drive unit.

It should be emphasized again that this example limits the change assessment only on the electrical power subsystem. In reality, implementation of starter-generator unit in place of conventional constant-speed drive (CSD) and AC generator assembly affects more than just the electrical power subsystem. The initiating changes to be made can be identified from the simplified illustration in Figure 68, which is based on the description of variable speed constant frequency (VSCF) starter-generator unit in [124].

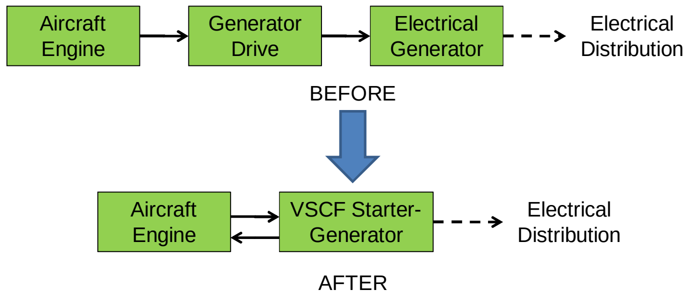


Figure 68: Required Changes for Starter-Generator Implementation

In this demonstration example, the effects are very much simplified but a more elaborate discussion on the installation impacts of starter-generator unit on current aircraft system architecture is presented in following Chapter 5. For the time being, based on Figure 68, initiating change components can be identified as generator drive unit and AC generator assembly. Because these components are interconnected to each other, they can either be assessed together or individually. For this example, they are considered together and the adaptability, extensibility and complexity risks are tabulated in Table 64 and Table 65.

Table 64: Example Calculation of Adaptability and Extensibility Risks

Proposed Redesign Change	Initiating Change Component	Adaptability Assessment		Extensibility Assessment	
		Impact	Cost	Impact	Cost
Electrical Starter-Generator	Generator Drive + Electrical Generator Assembly	6	8	1	6
TOTAL		6*8 = 48		1*6 = 6	
"Worst Case Scenario"		1*100 =100		1*100 = 100	
Normalized Score		48/100 = 0.48		6/100 = 0.06	

Table 65: Example Calculation of Complexity Risk

Proposed Redesign Change	Initiating Change Component	Parts Balance	Interface Balance
Electrical Starter-Generator	Generator Drive + Electrical Generator Assembly	-2	+2
TOTAL (*speculated total parts & interfaces)		**20/22* = 0.91**	**6/4* =1.5**
Ideal Score		2	
Normalized Score		**(0.91+1.5)/2 =1.21**	

If the change effects were to be contained within the locality of the initiating components without affecting the power distribution network that they are connected to, then a power converter unit have to be installed to regulate the generated electrical power to match the characteristics of the existing distribution network [49]. To date, technologies for VSCF starter-generator and power converter unit have already been developed [124]. Therefore, for adaptability assessment, the system modification is taken to be at SRL level 3 (based on Table 52), which corresponds to a risk rating of 6 as defined in Table 60. As for extensibility assessment, the effects are allowed to be propagated to electrical distribution network. This implies that the power converter does not have to be installed since the distribution wirings can be modified to match the generated power characteristics from the starter-generator instead. Because VSCF technology has been used and demonstrated on several transport aircraft systems like B737s and MD-90s [235], its SRL level for the extensibility assessment is given as 5 and this translates into a rating score of 1. For the cost rating, both adaptability and extensibility change cases seem to be a significant departure from current B737-200 aircraft system design. This is perceived to inflict notable changes to manufacturer’s production and supplier networks, and the cost ratings are assigned to reflect this discernment. Because the adaptability situation involves the installation of a power converter unit, it is assigned with a higher cost assessment than the extensibility condition. It should be noted that the expected effects from the modification to the electrical distribution network is not taken into account because the focus is on the initiating change components and not the propagated ones.

On the other hand, considering the proposed substitution of generator drive and electrical generator units (for both left and right systems) with starter-generator units, the number of total parts is reduced by two. Because the starter-generator unit also introduces new interlink within the aircraft engine unit (in both engines) for its starting mechanism, the interrelationship balance is a +2. Note that if the overall aircraft system is considered, the subsequent elimination of the existing pneumatic air starter mechanism for instance will also be factored in the overall interrelationship balance.

The plot of normalized evolvability metrics for the sample electrical power subsystem, with an equal weighting of 0.2 for each of them, is shown in Figure 69. In this weighting scenario, the overall evolvability risk is computed as 0.45.

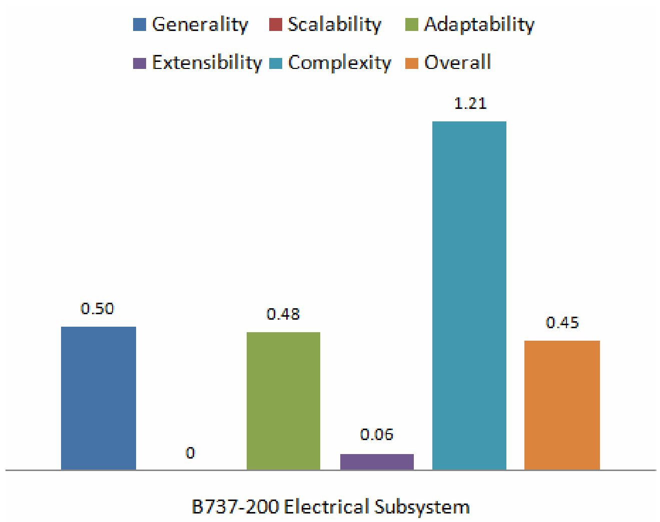


Figure 69: Evolvability Assessment for Equal Weightings

In general, Figure 69 can be interpreted as follows. First, a generality risk measure that is close to 0 indicates that most of the driving change requirements are expected to be met without modifying the existing design. For this example, the gross weight requirement is violated and this condition is reflected by the non-zero generality measure. On the other hand, it is possible to scale down the aircraft system design accordingly to satisfy each of the requirements independently and this is reflected by the zero scalability metric. Since this scalability measure is much lower than that of the generality metric, the redesign risk can be taken to be highly manageable. This indirectly indicates that the existing design is generally not overly inflexible to accommodate the required changes based on the notion that the system design scaling approach is the simplest form of product redesign efforts. In addition, based on the general practices of aircraft derivative development, the design scaling is often the first type of redesign approach that is considered when designers try to redesign the baseline aircraft to satisfy new driving requirements [296]. On the other hand, the adaptability risk measure is shown to be much higher than that for extensibility condition. This is a highly favorable change situation since it indicates that the redesign risk can be potentially reduced by propagating some change effects from the initiating components to the other components that is of lower redesign cost and difficulty. Last but not least, the complexity is assessed to imply whether the derivative design complexity is comparable to the existing baseline design. Since its value is above 1, it indicates that the complexity of the derivative design has increased from the original baseline. This is not a favorable situation but it should be noted that the elimination of several other parts and interfaces external to the electrical power subsystem is not accounted here, which should otherwise improve the complexity score.

In contrast, if the manufacturer highly favors minimum amount of changes, the weighting scenario can be modified accordingly. The assessment results shown in Figure 70 refers to the case where the weighting for the generality, adaptability and complexity metrics is assigned as 0.3 while the other system evolvability metrics are each assigned with a 0.05 weighting. In general, this weighting scenario indicates that it is highly preferred that the redesign process affects the lowest number of system components. As a result, the overall evolvability risk score has increased to 0.66, which reflects that the redesign risk level under such process preference is much higher than that under previous redesign scenario. This significant jump indicates that this might not be the most suitable baseline candidate if such redesign process preference is strictly imposed.

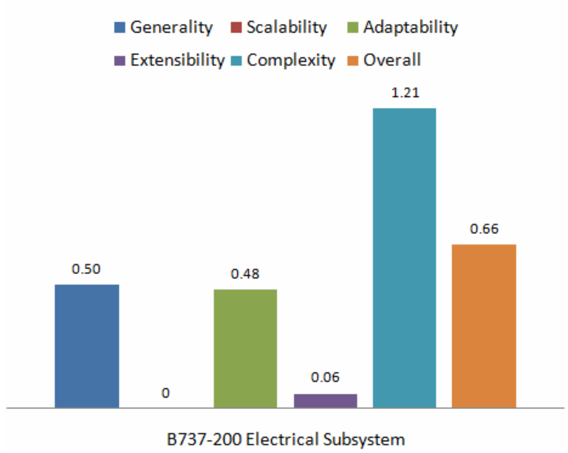


Figure 70: Evolvability Assessment for Minimum Affected Components

All in all, the summary of this baseline assessment process is illustrated in the following Figure 71.

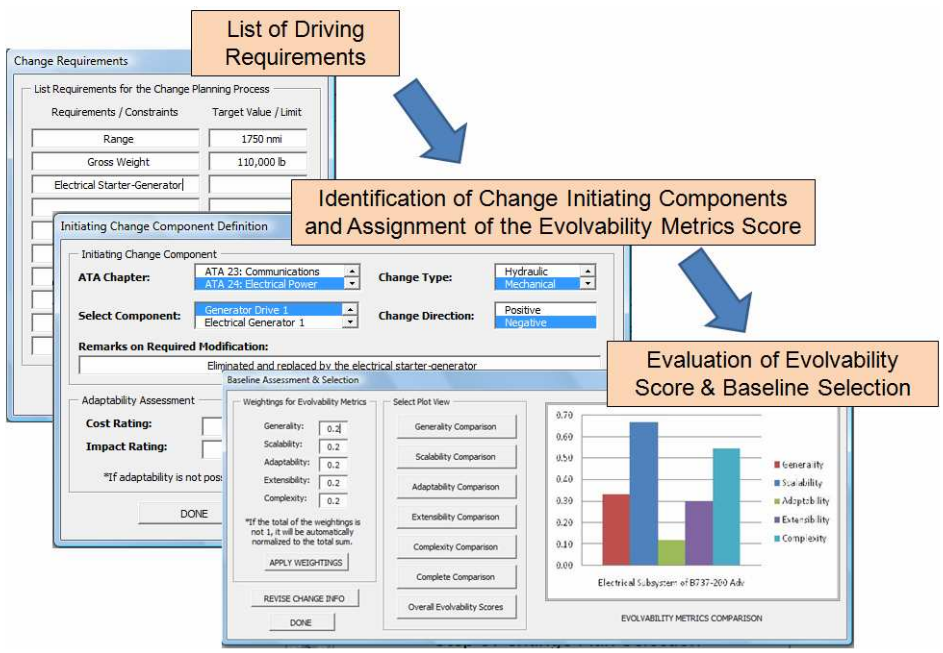


Figure 71: Baseline Assessment by SPEC Support Tool

4.2.3 Step 3: Change Plan Generation

As concluded in section 3.4.4, most available change planning methods and tools include no implementation strategy in their automated routines. They mostly assume the resultant product design architecture will remain the same as it is before, which means no addition or substitution of parts is allowed except for the initiating components. This is not always true as some revolutionary changes can take place and consequently modify the dynamics of interrelationships between the components. In addition, their program algorithms do not consider concurrent handling of the initiating engineering changes. Unless the effects from initiating change components are totally independent of each other, their interaction has to be considered during the planning process. By evaluating them separately, their combined effects are easily overlooked and end up being a crucial omission in reflecting the real extent of impacts from the proposed change implementation plan.

It can be implied from previous discussion that engineering change planning process for many complex products can be an overwhelming task. As suggested in the literatures, the potential change propagation paths in a product design is a factorial function of its number of elements [134], which can be extremely high for many complex products. Due to the numerous possible change propagation paths, it can consume a tremendous amount of time and efforts to generate all possible change plans. However, it has been observed in real industrial practices that the solution space for product redesign planning is often constrained by manufacturers, where some subsystems are not allowed to be modified due to company's management policy because they cost too much or their adaptation is too risky [115]. For instance, while developing their engine variants, designers in Perkins Engines Company reserved several parts of the baseline engine from being modified as their redesign was anticipated to cause significant increase in the development efforts and costs beyond the preferred limit [118]. This kind of resolution effectively reduces the amount of potential change propagation paths, hence the possible change plans.

From the understanding of this situation, a considerable amount of redesign planning efforts could be saved if designers are assisted with a proper scheme to reduce their product change solution space into a more manageable size for the practicality of their redesign analysis. In other words, the redesign planning can be made more efficient if all highly risky modifications are screened out early in the process. By doing so, valuable computational efforts could be saved from being spent on those risky change plans that would be eventually eliminated. In previous section 3.4.3, it has been discussed that the change role of each component can vary in different change situations and this leads to dissimilar change propagation paths. This means that a component does not have a pre-determined change behavior [115]. It can swap roles during engineering change process depending on the nature and magnitude of the propagated change effects, and its role in the integrated product architecture [175]. In general, four types of component change role are described as follow [115]:

- **Absorbers –** propagate no further changes after being changed
- **Carriers –** transferring change to others after being changed but neither reduce nor add to the complexity of the change problem
- **Multipliers –** expand the change problem further by making it more complex
- **Constants –** not affected and not causing changes

During redesign planning, designers have the choice to pass on the change effects from one component to another [116]. How a component within the product architecture is affected by the proposed changes depends on the way they are implemented [81]. With respect to different component change roles, the propagation path will be truncated when it reaches either a “constant” or an “absorber”. Since the least risky implementation plan is highly preferred, this knowledge is applied to determine the effective change solution space by “freezing” risky parts from being subjected to changes by the proposed redesign plan. This decision influences the ability of system components to accept and propagate engineering change effects, which can be exploited to control and reduce the likelihood of further propagated changes [121]. For instance, the components that are classified as risky will be assigned the role of a “constant”.

To decide whether a component is risky enough to be screened out from the change plan, it is evaluated from two aspects of redesign development risks. If the component has a high risk when being changed and at the same time propagates its change effects to other risky components, then it should not be changed. This decision is practically based on the objective to avoid unending change propagation, which is discussed in section 1.2.2 to be detrimental to the success of the redesign process. However, if the component has been determined to be the change initiating component, then it should not be designated as a "constant" or otherwise the redesign goals might not be able to be successfully achieved.

Observing the change decision-making process, it can be principally broken into several smaller "pairwise change comparison" sub-tasks where the decision to either propagate the change effects to the following component in the propagation tree or have the current component absorbs the impacts to itself is made based on the perception of which option leads to a better change risk situation. In other words, this relates to the causal influences of the change decision and its level of impacts. According to Saaty, one way to resolve this decision-making problem is the holistic approach where the factors and criteria that are involved in the procedure are identified and hierarchically ranked to highlight their transparent dependencies [276]. From this, their relative influence on the overall solution can be estimated and be used to aid the decision maker. The derivation of a prioritization ranking through pairwise comparison has been proposed in MAAP procedure in section 3.1.3, which is applied in the determination of relative importance for the metrics in its assessment process [339].

Based on observation of industrial practices, the change solution space for the proposed SPEC method is established by evaluating the relative change preferences of the aircraft subsystems and their relative potential of being affected by changes on other subsystems. This assessment should be made at the subsystems level instead of at the components level because the subsystems are mostly designed and developed independently by the various suppliers instead of solely by the primary aircraft manufacturer. It is unrealistic to ask them to "freeze" several of their product parts while changing the others since each supplier or subcontractor has their own design optimization scheme. Assuming that each subsystem comes as a single package from the supplier, it is more reasonable to decide if the subsystem as a whole should be considered for modification or not.

Coming back to the pairwise comparison problem, the relative ranking of the elements is derived through a prioritization matrix and to ensure the accuracy and consistency of the assessment (if it is done subjectively), the matrix should be reciprocal [275]. To generate and establish the priorities of the elements that have been measured based on the same rating scheme, their normalized ratio scale is used. As stated by Saaty, "ratio scales are the only means to generalize a decision theory into a case of dependence and feedback" [274]. In MAAP procedure, the normalized ratio scale is derived by dividing the score of each element to the overall sum [339], which can be seen as a slightly simplified version of Analytical Hierarchy Process (AHP) [274]. An example to highlight this procedure is depicted in following Table 66.

Table 66: Sample Calculation to Establish Relative Priorities

Component	A	B	C	Total Score	Normalized Ratio Score	Rank
A	1	5	0.2	6.2	6.2/23.5 = 0.26	2
B	0.2	1	0.1	1.3	1.3/23.5 = 0.06	3
C	5	10	1	16.0	16.0/23.5 = 0.68	1
TOTAL				**23.5**	**1.00**	

For the proposed SPEC methodology, the first prioritization matrix is applied to establish change preference between a pair of subsystems. This pairwise comparison answers the question of how preferable it is to change one particular subsystem against the other. This measure is made based on the qualitative rating scale in Table 67, which is modified from MAAP to suit the assessment focus at hand.

Table 67: Qualitative Scale for Pairwise Change Preference

Rating Scale	Description
10	The (row) is highly preferred to be changed than the (column)
5	The (row) is moderately preferred to be changed than the (column)
1	No preference in changing either the(row) or the (column)
0.2	The (column) is moderately preferred to be changed than the (row)
0.1	The (column) is highly preferred to be changed than the (row)

On the other hand, the second matrix is applied to derive the relative subsystems ranking with regards to their likelihood of being affected by the modification of other subsystems. In literature review, most available change methods are observed to assign this change likelihood value with the average number of times that the particular subsystem had been affected by changes made on other subsystem in the past. Moreover, it is often assumed that the change propagation path can affect only one subsystem at a time during the analysis [175], which is not truly representative of real industrial practices. The change propagation tree can split into several branches when more than one subsequent change is made in response to preceding component modification. To avoid these rather misleading assumptions, there is a need for a better way to derive the subsystems ranking according to their change susceptibility characteristics that is adequately unbiased towards unrelated past changes while being more representative of the change task at hand. In the proposed SPEC methodology, this is obtained using the modified prioritization ranking method.

The existing interrelationships between the subsystems are used as the measuring scale to reflect on their possibility to be changed. This indicates that the matrix is not derived qualitatively through the rating scale presented in previous Table 67 and it does not have to be a reciprocal matrix to ensure measurement consistency as it is derived quantitatively from the true state of the existing design. At this point, it is known that the change effects can propagate between two components if and only if they are interrelated to each other [174]. Based on this notion, an appropriate relative measure of their change relationship strength is the ratio of how many potential propagation links exist between them to their respective total of change links with others. If they are interconnected in so many ways to each other, it is highly likely that the modification made in either one of them will also affect the other. In contrast, the change effects are certainly not propagated if they have no interconnection at all between each other.

Once the rankings of the subsystems change likelihood and change preference have been derived, they are mapped together in the same plot that indirectly represents the available change solution space. Based on the standard or allowable limit set by designers, the subsystems that have a low change preference level but a high change potential rank can be classified as a “constant” for the change plan. It should be cautioned that proper care must be taken to not over-constrain the change alternatives by freezing unnecessarily too many components from being modified.

After the change solution space has been defined, all possible implementation alternative plans are extracted by going through the “reduced” CIM aircraft model. Several limiting algorithms have been proposed by available change propagation methods from previous background studies in section 3.4. By considering them and the objective of the proposed SPEC method, two change propagation guidelines are suggested as follows:

- If changes imposed on the same change attribute of a component come from the same initiating component twice, then the propagation is blocked. This is to avoid the propagation tree from going into the same loop over and over again.
- If changes imposed on an aspect of a component are conflicting with its previous effected changes, then the propagation is blocked. This is to avoid having infeasible change plan with respect to all governing requirements.

With these applied guidelines, the order of execution for each change requirement can be a significant factor in shaping up the change planning process. In typical product redesign development, several initiating engineering changes are often required and their effects are interconnected [120, 272, 332]. To fully explore the implementation planning, the process must be executed in all possible execution orders unless a priority order has been pre-set beforehand. In view of this, the maximum number of execution order is estimated as the factorial of the initiating components. If there are two initiating components A and B, then the first planning process is executed by considering A first and then B. In return, for the second process, B should be considered first. Similar action is also taken when the change effects propagation branches out into more than one path.

It is clear that this emphasis on execution orders greatly increases the amount of required computational efforts for the redesign planning process. The effects of execution order only become a factor during planning if different propagation paths cross each other. To avoid unnecessary computational efforts, incompatible change solutions should be first identified. If the change propagation trees from different initiating components are totally independent of each other, their execution order does not matter to the overall risks of the change plans. The full propagation trees are derived by assuming that no component will absorb the change effects imposed on them by preceding component. Hence the effects propagation will only stop when it encounters a "constant" that has been determined from the reduced change solution space or when it violates the previously defined propagation guidelines. If the proposed redesign changes from different sources on a component are found to be incompatible, only the execution order for those requirements is varied from their first point of conflict. Once all the change propagations have been mapped out, the change roles of the affected system components are varied to derive all possible change plans. In order to better illustrate this step of the proposed SPEC method, its sequence of phases is presented in Figure 72.

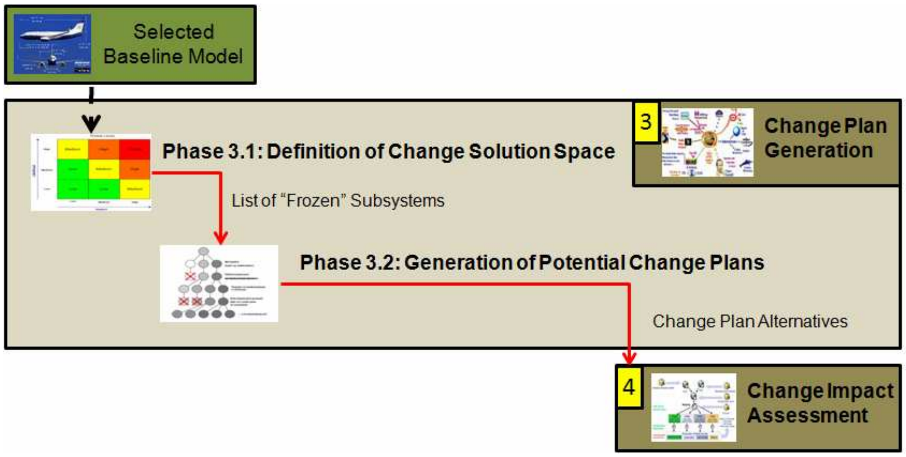


Figure 72: Overall Workflow for Step 3

To demonstrate this Step 3, consider again electrical power subsystem of Boeing B737-200 example. To further simplify the matter, the construction of prioritization matrices for change likelihood and preference is focused only on three subsystems in Figure 64: electrical power (ATA 24), auxiliary power (ATA 49) and turbine engine (ATA 72). It can be concluded from Figure 64 that the electrical power subsystem has one connection to APU where the auxiliary electrical power is supplied and one link each with the two engines that supply mechanical inputs to the generator drives. No interrelationship exists between the auxiliary power unit and the turbine engines. Furthermore, suppose that their total relationships with the other aircraft subsystems is known (which is hypothesized for the sake of the calculation). The prioritization matrix for change likelihood is constructed as in Table 68.

Table 68: Example Evaluation of Subsystem Change Likelihood Score

	Electrical Power	Auxiliary Power	Turbine Engine	Total Connection (*speculated)	Total Score	Normalized Score
Electrical Power	1	1/6 = 0.17	2/11 = 0.18	30*	1.35	0.39
Auxiliary Power	1/31 =0.03	1	0	5*	1.03	0.30
Turbine Engine	2/31 = 0.06	0	1	10*	1.06	0.31
				TOTAL	3.44	1.00

Based on Table 68, a higher total score means that the corresponding subsystem is more susceptible to be changed. For instance, the first row of the matrix corresponding to the electrical power subsystem can be interpreted as follows. The measurement value of 1 is assigned in the first column to signify that any proposed change on the electrical power subsystem (column 1) will undoubtedly affect its current design. On the other hand, if the current auxiliary power unit (column 2) requires modification, the measurement value of 0.17 implies an estimated 17% chance that the change will also affect the electrical power subsystem (row 1). This is based on the assumption that the auxiliary power unit has five distinct interlinks with other subsystems and one of them is linking to the electrical power subsystem. An extra value is added to the total number of links for the change likelihood estimation to represent the possibility of no propagated change. This extra "link" measure ensures that the derived change likelihood is mutually exclusive [175]. While the actual modification cannot be specified at this point as the change plan is not yet available, this estimation is based on the notion that if the change effects are to be propagated, they will have to be made through the existing interconnections that the subsystems have with each other. A higher amount of interrelationships with other subsystems means higher chances for the change effects to be passed through the subsystem.

Meanwhile, the ranking of subsystems change preference is derived through prioritization matrix in Table 69. Recall that the qualitative change preference for the subsystems pair is assigned based on the rating scale defined in previous Table 67.

Table 69: Example Evaluation of Subsystem Change Preference Score

	Electrical Power	Auxiliary Power	Turbine Engine	Total Score	Normalized Score
Electrical Power	1	5	10	16.0	0.56
Auxiliary Power	1/5 = 0.2	1	10	11.2	0.39
Turbine Engine	1/10 = 0.1	1/10 = 0.1	1	1.2	0.04
			TOTAL	**28.4**	**1.00**

Based on Table 69, a higher total score means the subsystem is preferred to be changed in comparison to other subsystems. For instance, the first row of the matrix corresponding to the electrical power subsystem can be interpreted as follows. Referring to Table 67, a value of 1 is given to the first column to indicate a similar level of change preference of the electrical power subsystem to itself. Conversely, the value of 5 in the second column indicates a moderate change preference for the electrical power system over the auxiliary power unit. This indicates that given a choice, designers moderately prefer to modify the electrical power subsystem rather than the auxiliary power.

A simultaneous mapping of the subsystems change likelihood and preference scores is depicted in Figure 73. The change role for turbine engine is designated as a “constant” because its level of change preference is extremely low, indicating its perceptively high change risk in relative to the others. These measures are not to be taken as “absolute” but should be treated as a relative comparison among considered subsystems or components. With this decision, possible change plan alternatives that have been generated based on the initiating changes identified in Step 2 are presented in Table 70. Notice the difference in the component change roles for the different change alternative plans.

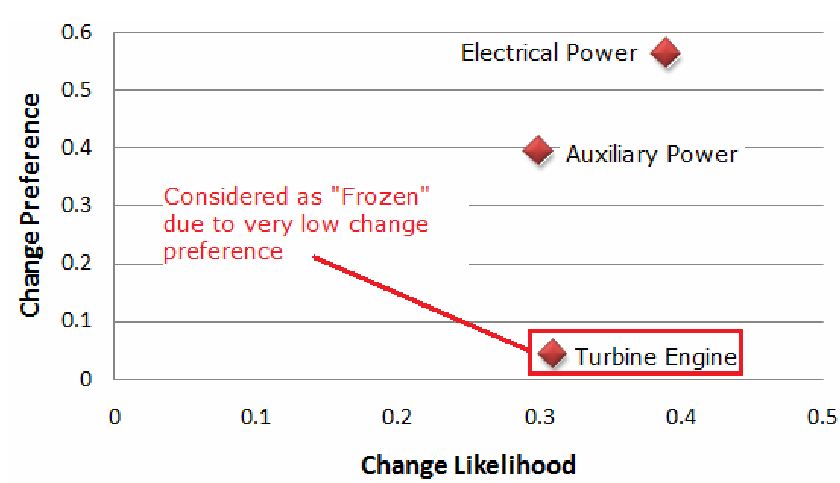


Figure 73: Example Subsystem Change Likelihood-Change Preference Mapping

Table 70: Example Generated Change Plans

Plan	Modified Component	Change Role	Change Remarks
1	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	Absorber	Combined into a starter-generator unit. Because the turbine engine is “freeze” from being modified, the starter-generator has to fit the current mechanical drive input requirement and still produce the same required amount of electrical power supply.
2	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	Carrier	Combined into a starter-generator unit. Produce electrical power supply based on the existing amount of available mechanical input from the turbine engine.
	AC Bus (1 and 2)	Absorber	Include a power converter unit to match the characteristics of the electrical-based components.
3	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	Carrier	Combined into a starter-generator unit. Produce electrical power supply based on the existing amount of available mechanical input from the turbine engine.
	AC Bus (1 and 2)	Carrier	Changed to match the characteristics of the produced electrical power supply.
	Affected electrical-based components	Absorber	Changed to match the characteristics of the distributed electrical power supply.

The summarized illustration of this change plan generation process is shown in Figure 74.

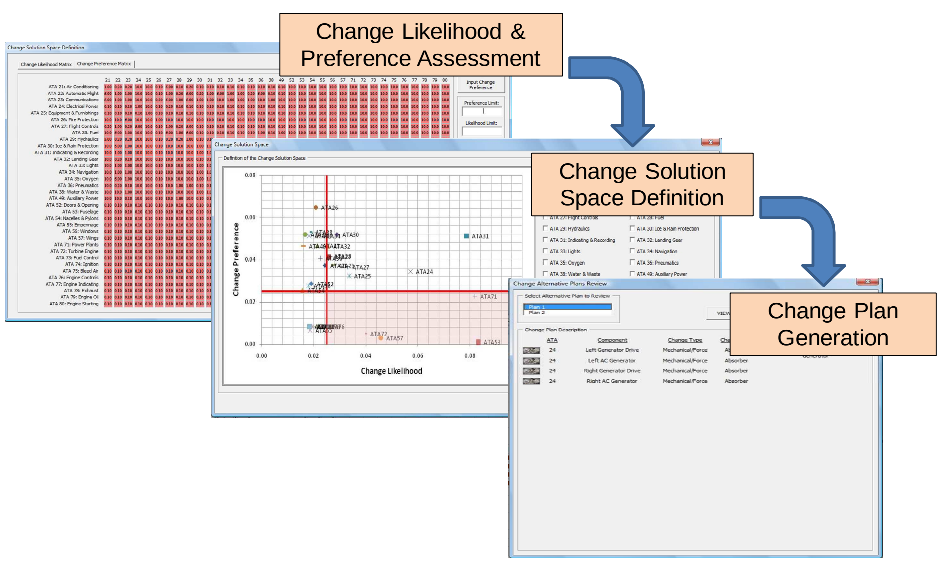


Figure 74: Change Plan Generation by SPEC Support Tool

4.2.4 Step 4: Change Impact Assessment

Up until this point, the possible change implementation alternative plans have been made available from Step 3. The main objective for this step is therefore to assess their possible impacts on both the development process and the performance capabilities of the product. In general, before any modifications can be properly decided to be acceptable, its overall effects including required efforts in redesign planning, scheduling and resourcing have to be estimated [152]. In view of this, designer who is the change initiator or implementer is responsible to consider all possible propagated effects before deciding the right trade-offs during change planning [83]. As emphasized by available standards in product industries, the most critical part of change planning process is the impact prediction [176]. However, none of them outlines the suggested change impact analysis methods or tools as part of their guidelines [273].

Based on literature review, the analysis of change effects from the perspective of product development process can be approached from the level of development risks associated with the implementation plan. In section 3.4.4, CPM has been selected as the best change method with the most proper impact assessment scheme. It uses a simple redesign change risk calculation that is widely applied within the product risk management field [81]. In reference to this CPM evaluation scheme, the measure of redesign development risks is calculated as follows:

$$Process\ Risk\ Index = \frac{\sum_{affected\ componentt}\left[Impact\ Level \times Cost\right]}{Maximum\ Calculated\ Process\ Risk} \quad \text{Equation 18}$$

In this case, all components within each implementation plan can be perceived as already being “chosen” for modification and hence their change likelihood is taken as 1. It should be noted that this scheme is closely similar to the one applied to estimate adaptability and extensibility risks in Step 2. To scale this process risk measure for better comparison, it is normalized to the maximum calculated value between the change alternative plans.

On the other hand, resultant changes made on the aircraft design should also be linked to its overall system performance. It is important to not only have a viable redesign process but also a derivative aircraft that can satisfy all its operational requirements. For instance, a spatial change on modified subsystem components can affect the aircraft gross weight and subsequently affects its high-level performance. For this proposed SPEC method, it is assumed that the relationships between subsystem component parameters and high-level aircraft system performance metrics are available prior to its initiation. In section 3.3.4, the benefits of using RSM to capture the performance impacts due to design engineering changes have been discussed. If the subsystem-system relationships are not available and the simulation analysis tool for aircraft performance is accessible, RSM is a good option to derive them. All in all, by translating the change effects into appropriate estimates of the performance factors, technical feasibility of the derivative aircraft can be analyzed against its operational requirements. In cases with multiple constraints, the metrics can be combined into an overall evaluation factor as defined by following performance index.

$$Performance\ Metric = \begin{cases} \left(\dfrac{resultant\ \ performance\, level}{required\ \ performance\, level}\right) & if\ \ maximum\, is\ \ preferred \\ \left(\dfrac{required\ \ performance\, level}{resultant\ \ performance\, level}\right) & if\ \ minimum\, is\ \ preferred \end{cases}$$

Equation 19

$$Overall\ Performance\ Index = \frac{\sum_i \left[Performance\ Metric\right]_i}{n}$$ Equation 20

where i = considered performance metric
n = number of considered performance metric

Once the redesign development risk and performance indexes for each alternative change implementation plans have been obtained, the selection of the best group of plans can be made. All in all, the tasks involved in this change impact analysis phase of the proposed SPEC method are summarized in Figure 75.

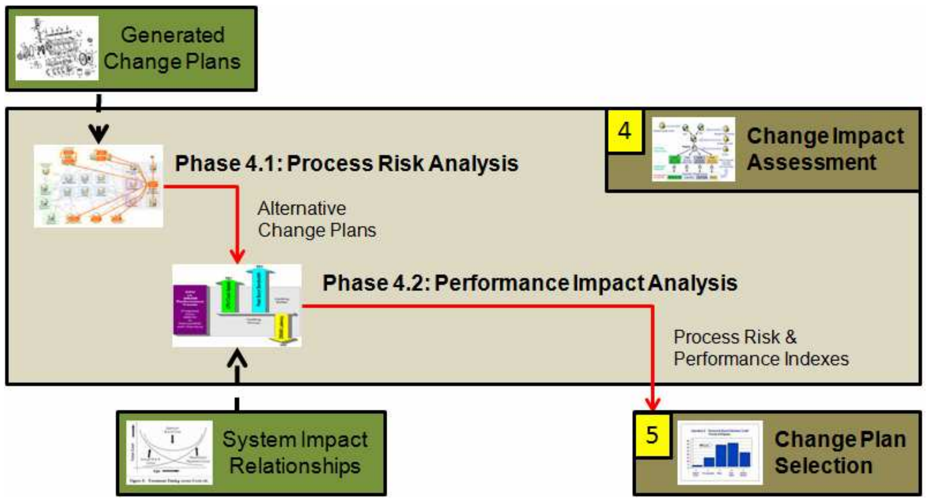


Figure 75: Overall Workflow for Step 4

To demonstrate the procedures involved in this Step 4, the generated change alternative plans for the example electrical power subsystem of B737-200 aircraft that are tabulated in Table 70 are analyzed. Calculation for the process risk and performance indexes that are associated with them is presented as follows. This sample calculation is formulated purely by intuition and should not be taken as a true representation of the present state of industry. Instead, the main goal here is to simply demonstrate the procedures in this Step 4. With that in mind, the process risk evaluation is presented in Table 71.

Table 71: Example Process Risk Calculation for Alternative Change Plans

Plan	Modified Component	Change Role	Process Risk Calculation	Process Risk Index
1	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	Absorber	6*8 = 48	48
2	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	Carrier	1*6 = 6	42
	AC Bus (1 and 2)	Absorber	6*6 = 36	
3	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	Carrier	1*6 = 6	42
	AC Bus (1 and 2)	Carrier	1*6 = 6	
	Affected electrical-based components	Absorber	3*10= 30	

From Table 71, the estimated redesign process risk for plan 1 should be similar to that calculated for adaptability risk in Step 2. This is because for that particular change plan, the change role of the combined "generator drives and AC generators" is assigned to be an absorber. This indicates that the initiating changes have to be accommodated within these parts only, which matches the condition for adaptability. On the contrary, for plans 2 and 3, their role is switched to a "carrier" and the propagation of their change effects is allowed to other components. This condition is similar to extensibility characteristic for system evolvability measure and hence it can be observed that the estimated process risk in this case is the same as the valuation of extensibility risk in Step 2. Another highlight of Table 71 is the fact that the average process risk for plans 2 and 3 are equal to each other although the former involves less affected components. If the process redesign risk is the sole selection criterion, plan 2 is generally the most preferable change proposal amongst the three options because it is less risky than plan 1 and requires relatively less redesign efforts than plan 3. However, it should be noted that the process risk evaluation for plan 3 in this example has been highly simplified (especially with regards to affected electrical-based subsystems) in order to better demonstrate the calculation procedure.

On the other hand, the calculation of aircraft performance impacts that are caused by the design modification requires the established relationships between the affected subsystem parameters and the high-level system performance metrics under interest. Recall driving requirements that are defined for this example in Table 62. Let's just focus on the gross weight requirement for this demonstration purpose and the speculated weight effects for each of change implementation plan are presented in Table 72. Again, these estimated values are purely derived based on speculation.

Table 72: Example Performance Impact Calculation for Alternative Change Plans

Plan	Modified Component	% Weight Effects *speculated	Total % Weight Effects *speculated	Performance Index
1	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	- 2%	- 2%	114000/113680 = 1.002
2	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	- 2%	- 1.9%	114000/113796 = 1.002
	AC Bus (1 and 2)	+ 0.1%		
3	Generator Drive (1 and 2) + Electrical Generator (1 and 2)	- 2%	+ 1%	114000/117160 = 0.973
	AC Bus (1 and 2)	+ 1%		
	Affected electrical-based components	+2 %		

As can be implied from the notionally constructed Table 72, plan 1 corresponds to the highest weight reduction that will help the B737-200 aircraft derivative to be closer to the target takeoff gross weight. On the other hand, plan 3 corresponds to the worst weight effects since an additional 1% weight is expected due to installation of power converter unit for each electrical-based subsystem. Change implementation plan 2 corresponds to a slightly lower total weight reduction than plan 1 due to installation of the central power conversion unit.

All in all, both process risk and performance indexes are passed to the following Step 5 where the alternative change plans are compared to determine the best among them. The summary of this change impact analysis process is depicted in following Figure 76.

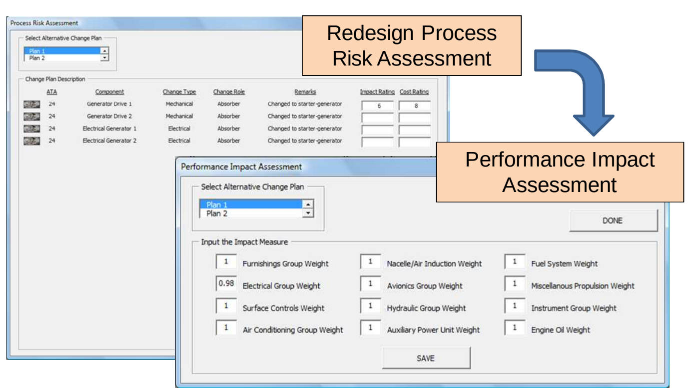


Figure 76: Change Impact Assessment by SPEC Support Tool

4.2.5 Step 5: Change Plan Selection

So far, the alternative change implementation plans that can possibly satisfy the driving requirements have been derived back in Step 3. For this Step 5, the main focus is to select the best among the possible redesign plans and this decision is made based on the results of the change impact analysis done in Step 4.

It is known from the literature study that the choice of redesign plan is highly influenced by its potential consequences [39]. As argued before, the decision-making process should consider the estimated effects from both the process and product performance viewpoints. Unfortunately, the available change methods that have been identified in the literature do not directly discuss or emphasize on the latter aspect of the redesign effects. In general, the development process risk is preferred to be as low as possible while the performance of the resultant design needs to be as close as possible to the target requirements. For the proposed SPEC method, these preferences correspond to the highest value for the process risk and performance indexes that are defined in previous Step 4. Moreover, the change plan selection process can be visually aided by the redesign performance-risk plot. It is suffice to say that the group of the change implementation plans that is contained within the pre-set limits of the development process risk and performance constraints will make up the potential change proposals for the required modification.

Coming back to the electrical power subsystem example, the corresponding performance-risk plot for its generated change alternative plans is presented in Figure 77. As can be observed from the figure, the weight performance of the redesigned aircraft in plan 3 fails the performance constraint since it has a performance index less than 1 (if multiple target performance metrics are combined into this index, care must be taken before making this conclusion) although its process risk is more favorable than plan 1. On the whole, plan 2 seems to be the best option due to its comparable weight benefits but significantly lower process risk to those of plan 1. In addition, from the assessment of this plot, the possible redesign trade-offs can be identified and formulated to improve the generated plans in the case when none of them is perceived as acceptable.

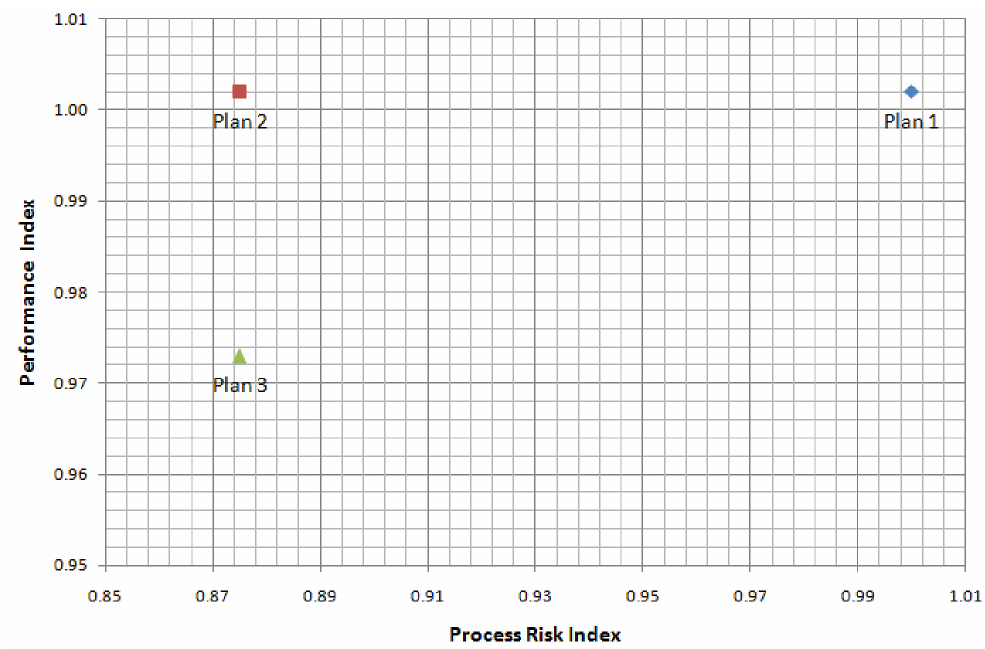


Figure 77: Sample Performance-Risk Plot

In summary, the tasks involved in this final selection step for the proposed SPEC method are depicted in Figure 78.

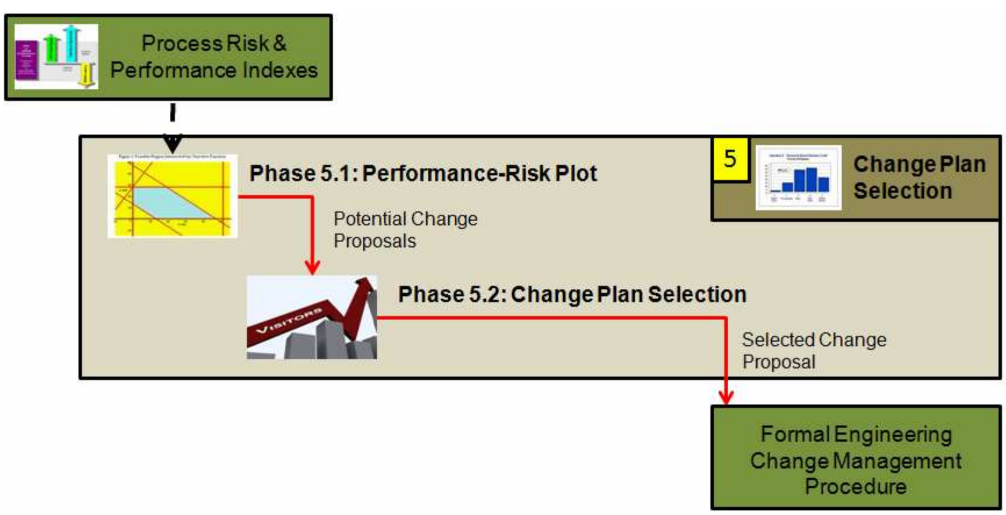


Figure 78: Change Plan Selection Step in Proposed SPEC Method

The depiction of this selection in the SPEC support tool is shown in Figure 79.

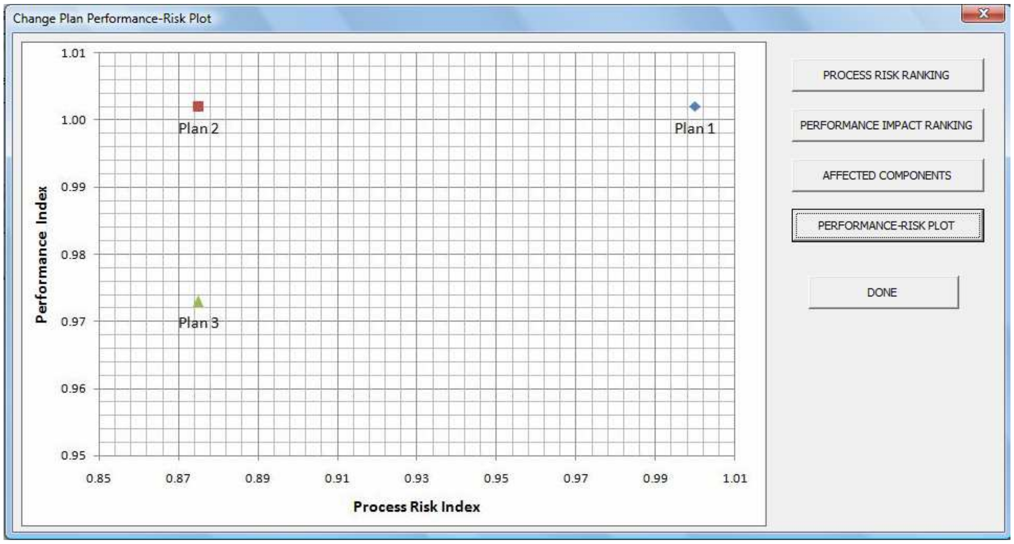


Figure 79: Change Plan Selection Environment by SPEC Support Tool

4.3 Summary of Proposed Methodology Activities

With the steps of the proposed SPEC methodology have been detailed out, their summary of activities is presented in Figure 80.

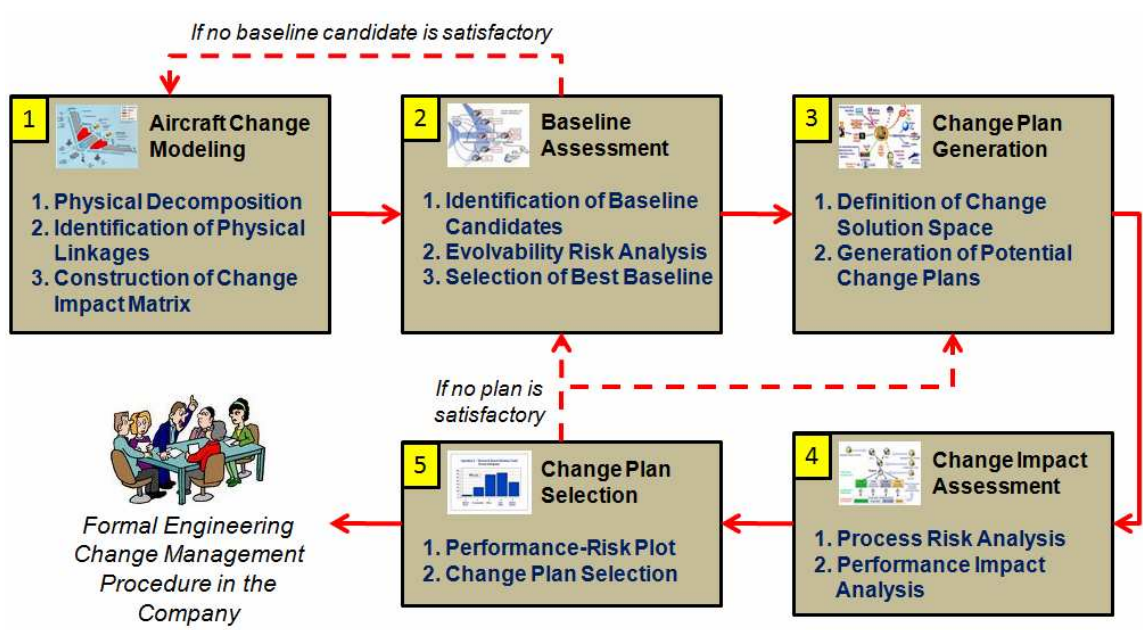


Figure 80: Activities in Strategic Planning of Engineering Changes (SPEC) Method

From the discussion of available change frameworks and approaches, the feedback links are added to represent possible iterations of the change planning process as indicated in Figure 80. Firstly, the feedback link from baseline assessment step into aircraft change modeling step is required when the preliminary analysis fails to identify a suitable baseline among the initial candidates. Once the new candidates are identified, they have to be modeled before they can be studied and this is the reason behind this first feedback link. Secondly, the iteration of the redesign planning process is necessitated if none of the generated change implementation plans satisfy the criteria set for their approval. In this case, there are basically two main approaches that can be done to improve the situation. By selecting another baseline aircraft that is more relevant, the change solution space is practically modified and this opens up new opportunities for better implementation plan alternatives. On the other hand, the redesign solution space can also be improved by alleviating the change planning constraints without selecting a new baseline design. Both of these options are represented by the feedback links from change plan selection step to baseline assessment and change plan generation stages, respectively.

It should also be realized that the way this proposed SPEC method is outlined maintains the generality of its application, which indicates that it can also be applied to other types of products instead of aircraft. As implied from Figure 80, its application requires several detailed inputs from designers or product experts. These include accurate assessment of change tolerance and SRL levels for each identified component, proficient translation of driving requirements into initiating changes and extraction of relationships between the system performance metrics and the component parameters. The accuracy of results from this proposed methodology will greatly depend on the quality of these inputs.

Overall, as detailed in the motivation of this research study, this method is developed as a change decision aid for designers to plan their aircraft modification process. This helps to fill the current absence of change planning methods and tools, and in the bigger picture it also helps manufacturers to identify related development risks and required processes with their sub-contractors. By knowing more details about their aircraft redesign aspects, manufacturers can have a better control of their designs by providing more complete specification to their sub-contractors and avoid any system integration problems later on. The knowledge gained from this planning process enables the return of the design control to the primary aircraft manufacturers rather than letting their designated sub-contractors or suppliers control and dictate their design evolutionary paths.

4.4 Comparison to Existing Methods and Tools

From the above discussion, the procedure for each step of the proposed SPEC method has been formulated in reference to several existing methods that are identified in Chapter 3. This section is intended to discuss the similarities and differences of these methods to the final procedures in the proposed SPEC method. The objectives for this discussion are to highlight the improvements that are achieved to address the previously identified gaps in aircraft redesign process and to distinguish the contributions of this proposed method.

In section 2.3.7, "change planning process" method has been evaluated to be the current best among the identified existing product redesign and engineering change management methods. A high-level comparison between its procedures and those of SPEC method is depicted in Figure 81. Furthermore, the offered advantages and identified shortcomings for the change planning process, which are discussed in Chapter 1, are listed again in Table 73.

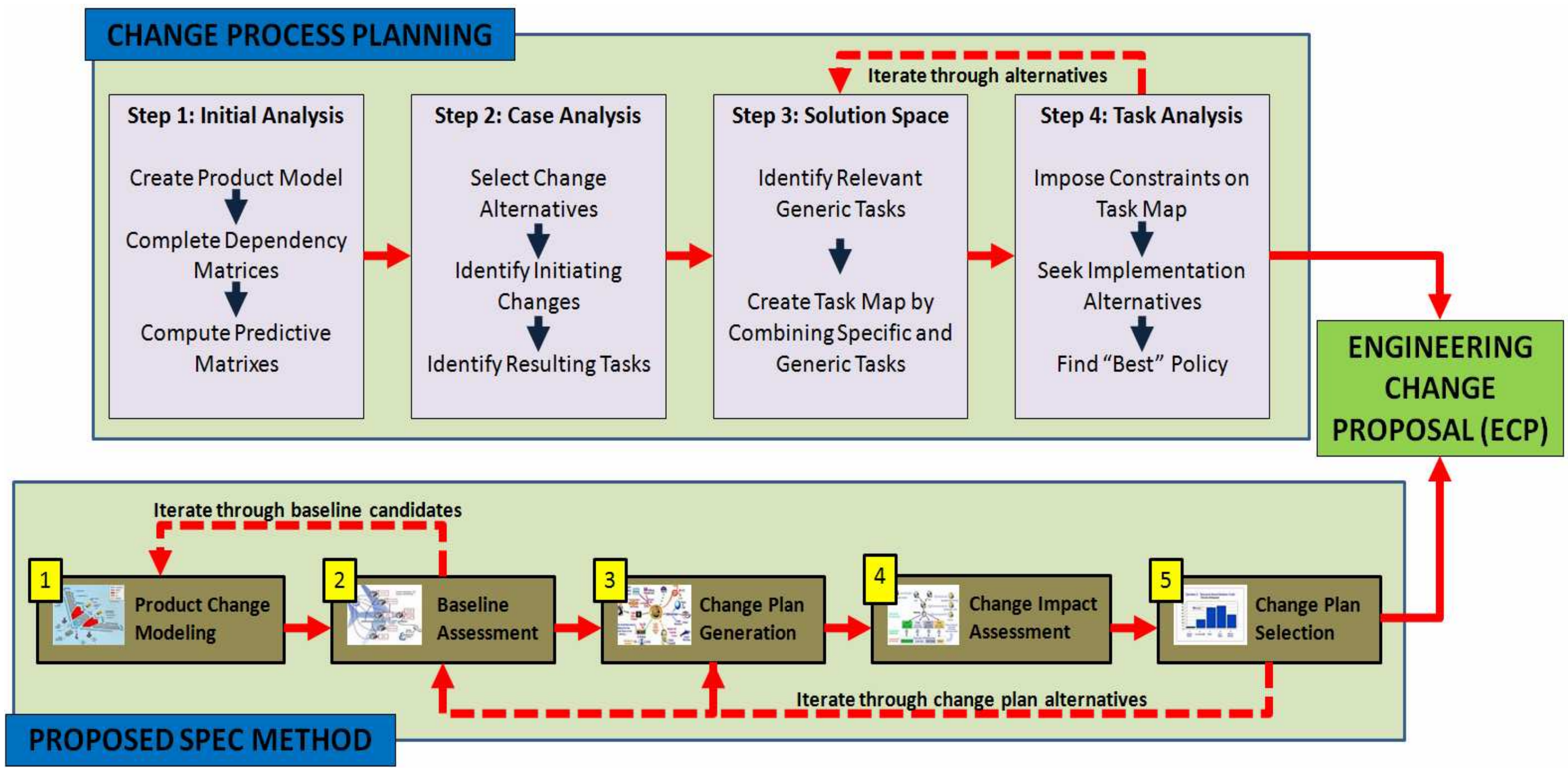


Figure 81: Comparison of Change Process Planning to SPEC Methodology

Table 73: Advantages and Disadvantages of Change Planning Process

Advantages	Disadvantages
• Provide a structured workflow for redesign planning process • Provide structured means to track change propagation and analyze the impacts on development process	• Lack emphasis on strategic redesign decision-making • Lack emphasis change impact analysis on product performances • Do not support baseline assessment • Do not support simultaneous changes planning

As implied from Figure 81, the proposed SPEC method maintains a structured workflow for the redesign planning process. As described in previous section 4.2.3, the generation of alternative change plans in SPEC method involves proper tracking of potential change propagation paths and analysis of their impacts. On the other hand, the implementation of SPEC method is supported by a strategic redesign approach that considers the effects on both development process and performance metrics of the derivative aircraft, which has been identified to be missing from procedures of the "change planning process" method. Furthermore, the baseline assessment and the simultaneous change planning capabilities are also incorporated into the procedures of the proposed method, which further improves its application for the intended objective of this study. All in all, the improvements that have been made for the proposed SPEC method resolve the identified disadvantages of the "change planning process" method for the aircraft redesign process.

The comparison between the reference methods or tools and the proposed SPEC method in several of its main application areas is further presented in the following sections.

4.4.1 Aircraft Change Modeling

Based on assessment in section 3.2.6, product dependency model by Rutka et al. [273] is taken as the current best approach to be the main reference in the development of aircraft change model for the proposed SPEC method. From discussion in section 3.2.5, its model construction is mainly intended for automated change propagation prediction and tracking. Using the defined set of attributes in Table 33 for each component, the potential change propagation paths are identified. However, because the SPEC method is not intended to be an automated change plan generator like most available change support methods and tools, the scope of its modeling procedure is not required to be as extensive as that of the product dependency model. Based on this realization, some elements of the product dependency model are appropriately modified to fit the purpose of the proposed method.

An aspect that is of significant concern for the change modeling procedure is the balance between model details and required amount of efforts for the model construction. Recall that the main goal of the proposed SPEC method is to be a decision-making aid for designers while planning for their product redesign. Therefore, its application will be interactive to their inputs. Instead of trying to create an extensive database of change effects propagation that covers all possible change situations as supposed by the product dependency model, it is adequate for the aircraft change modeling procedure in the SPEC method to highlight the existing interconnections between the components without really specifying their type or level of change impacts. Such change details are expected to be input by designers or system experts during its run-time, which will better reflect on the present situation of the change tasks at hand rather than pre-defined database that might be inaccurately derived from historical change data. To ensure all possible means of the change propagation are covered, the aircraft model is constructed based on the taxonomy of system element interactions that is discussed in section 3.5.2. In addition, from the product dependency model, the component change tolerance is also an important attribute that will indicate whether the engineering change effects can be propagated between the interconnected components. The taxonomy of system element interactions has already been used in several product modeling approaches, albeit indirectly. The inclusion of change tolerance level is clearly one of the criteria that make product dependency model the better approach in accurate prediction of change effects propagation in comparison to other identified methods. By combining these two model attributes, the aircraft change modeling procedure for the SPEC methodology is accomplished with considerably less amount of efforts and manageable model size but without sacrificing its accuracy to predict the change effects propagation. To conclude, the comparison between the aircraft change modeling approach that is used for SPEC method and the product dependency model is presented in Table 74.

Table 74: Summarized Comparison of the Change Modeling Procedure

Required SPEC Characteristics	Product Dependency Model	Change Modeling Step in SPEC	Remarks
Provide change propagation tracking scheme	Predict and track the change effects propagation mainly through the type and the level of the modification	Predict and track the change effects propagation mainly through the type and the level of the modification	The aircraft change modeling approach in SPEC follows the basic notion of the change effects propagation in the product dependency model
Balanced model details and modeling efforts	The model size might be too large with the extensive change database definition and the amount of the required modeling efforts can be high. The accuracy of the change propagation can be compromised by the pre-defined change database	The model size and the amount of required modeling efforts are controlled through the use of the taxonomy of system element interactions and the change tolerance level without compromising the accuracy of the change propagation prediction	The use of taxonomy of system element interactions and the inclusion of the change tolerance level for each component ensure a manageable model size. It suits the interactive application of the proposed SPEC method

4.4.2 Baseline Assessment

In previous literature review, no known formal method is found to be directly focused on the assessment of baseline suitability for redesign, particularly from the viewpoint of its architecture. There are nonetheless several standard definitions that are proposed to guide the evaluation process but it is acknowledged that having a structured, quantitative means to select the product baseline is more beneficial [311]. With respect to the characteristics outlined for the SPEC method based on the recognized gaps of current redesign practices, quantitative system evolvability is perceived as the best available method in section 3.1.4.

In section 3.1.1, the quantitative system evolvability method has been discussed to offer a structured evaluation scheme for the system redesign through its definition of four main evolvability metrics: generality, scalability, adaptability and extensibility. The definition for these metrics, as presented in previous Table 13, is closely related to the capability of existing system architecture to accommodate the required changes. However, the missing aspect that is essential in evaluating the incremental design efforts is the relative measure of the resultant design complexity in comparison to its predecessor baseline. In theory, if the baseline system is highly flexible, changeable and enhanceable, its design complexity will not drastically increase after its modification. Furthermore, the proposed evaluation metrics in this method is mainly focused on high system level. This can potentially lead to misleading conclusions as the generalization of required redesign costs and efforts to those at the higher system level does not appropriately capture the full extent of their characteristics.

In the SPEC methodology, the four assessment metrics defined in the quantitative system evolvability method are maintained due to their goodness in capturing the essences of the redesign approach from the perspective of existing system architecture. However, to cope with its inherent deficiencies regarding the resultant design complexity and the absence of proper evaluation scheme for its metrics, the formulation of the baseline assessment step for the proposed SPEC methodology also includes some elements of MAAP method, which has been discussed in section 3.1.3. Specifically, an additional system evolvability metric called "complexity" is introduced and a more structured calculation suggested in MAAP is referenced for the metrics evaluation. While the system metrics in MAAP are not directly similar to those defined in the quantitative system evolvability method, they can be easily associated to each other and this enables the tailoring of evaluation scheme based on the suggested MAAP approach. By doing so, the final baseline assessment step in SPEC method can be perceived as a combination of quantitative system evolvability and MAAP methods, which inherits the offered advantages from both methods but at a much improved performance than that of their individual application. On the whole, the key comparison of the baseline assessment procedure in the proposed SPEC method and the quantitative system evolvability method is summarized in Table 75.

Table 75: Summarized Comparison of the Baseline Assessment Procedure

Required SPEC Characteristics	Quantitative System Evolvability	Baseline Assessment Step in SPEC	Remarks
Provide a structured baseline evaluation scheme	Evaluate the suitability of the aircraft system for redesign based on four evolvability metrics: generality, scalability, adaptability and extensibility	Evaluate the suitability of the aircraft system for redesign based on five evolvability metrics: generality, scalability, adaptability, extensibility and complexity	The inclusion of complexity metric based on MAAP method enables the evaluation of relative design complexity between the derivative aircraft and its baseline
Suitable for considered scope of redesign process	The metrics evaluation is made at the high system level through the suggested DSEA qualitative rating scale	The metrics evaluation is made directly at the system level where the changes are being made using the evaluation scheme proposed by MAAP	The evaluation focus on directly affected aircraft components and the application of calculation scheme based on accepted standards in the industry provide more reliable assessment results

Table 75: Summarized Comparison of the Baseline Assessment Procedure (cont.)

Required SPEC Characteristics	Quantitative System Evolvability	Baseline Assessment Step in SPEC	Remarks
Scalable to specific engineering change evaluation	The method is originally intended for the new product development efforts	The definition of the evolvability metrics has been modified to suit the application for the aircraft redesign process based on the available system standards	The modified definition of the metrics enables them to be properly used to assess the suitability of the aircraft design to undergo the proposed modification

4.4.3 Change Plan Generation

Most available change methods have been found to lack any implementation strategy and this situation is mainly due to the fact that their application scope does not include being a decision-making aid for designers. In other words, their application is more focused on documenting the redesign plans that have been manually determined by designers rather than aiding them to decide on the best way to implement the required modification into the product system. A high reliance is put on the experiences of product design experts to manually try to minimize the change effects [79].

On the other extreme, several change methods and tools are developed as an automated change plan generator. In this application, no interaction with designers or experts is involved during the generation of the change implementation plans. The planning is automatically done based on the product change database. It appears that these methods rely heavily on historical data that tends to lead to a biased change propagation analysis. As the characteristics of the engineering changes often differ from case to case, taking the average historical measure to estimate the change likelihood and impact metrics without considering the differences in the actual situation of the change problems can mislead the overall risk evaluation. It is suggested that the automated change propagation analysis is applied only in cases with well-defined and static product structures [152] since most of the automatically generated change plans assume that the physical product components in existing architecture will remain the same as it is before the proposed initial modification. This is not always true as some revolutionary changes can take place and consequently modify the dynamics between the product components.

In section 3.4.4, change prediction method (CPM) has been evaluated as the current best to be applied in generating and assessing possible change implementation plans. It was suggested that CPM is one of the most advanced change propagation method that is presently available [273]. From its description in section 3.4.3, CPM predicts potential change propagation paths based on the constructed product DSM model that contains the information on its components interconnections. In short, the method assumes that any existing connection indicates that the change effects will be propagated between the two interlinked components. However, it has been argued that this is not always the case since change propagation also depends on the type and level of the modification. On the other hand, once change propagation paths have been mapped out, the overall risk is estimated by CPM using the risk calculation scheme that is widely used in product risk assessment field. Briefly, the redesign risk is measured as the product of change likelihood and change impact level. Even though the risk estimation scheme is widely accepted in the field, problem arises when the measures for change likelihood and impact level are derived through historical change data. Due to the fact that the condition of change task at hand might easily be different than previous change cases, the analysis results can be misleading and hardly representative of the present change problem. Last but not least, because CPM is not developed to be a change plan generator, it is not equipped with the ability to explore change solution space or to simultaneously analyze different initiating changes at a time.

For the change implementation planning procedure in the proposed SPEC methodology, the main interest is to be able to fully explore the change solution space and extract all possible change implementation plans for the required modification. To accomplish this, the appropriate change solution space must be defined. In theory, the solution space is made up by the decision to either allow a component design to be affected by the initiating changes or not. While this practice is evident in the industry, no known method is found to formalize this idea. From the understanding that such decision is often made by designers based on the business aspects of product manufacturing rather than the design technical aspects, the change solution space defined in the proposed SPEC method is constructed based on change likelihood and preference measures. Change likelihood corresponds to the measure on how likely a component will need to be modified from the changes made in others. Because it is known that the primary means for change effects propagation is the connection between the components, which has been acknowledged by many available change methods or tools, the component that has many links to the others will have a higher possibility to be affected by any modification. Moreover, to capture the preference of designers (or the company's policy) in modifying the product components, their inputs are used to sort the components based their change preference. Overall, these two relative rankings are derived using the concept of ratio scales that has been suggested for similar type of assessment problems [274]. This information helps to aid designers in deriving the change solution space to be considered for the implementation planning.

Based on the defined change solution space, the possible change implementation plans can be generated without increasing too much computational efforts by eliminating the infeasible or unfavorable alternatives. While the core idea in CPM to predict the change propagation through existing interconnections between the product components is good, its execution is improved for the SPEC methodology by considering the change type and level. This is formulated in reference to CPA method, which is discussed in section 3.3.1.

With the inclusion of these propagation criteria, the prediction accuracy is improved. To fully explore the change solution space in order to generate change plan alternatives, the component change roles can be varied. Although it is acknowledged that the component's change role can be different in different change propagation situations [115], no known formal method is found to take full advantage of this conception to study the possible implementation plans. By allowing the change roles to vary, several alternative redesign plans can be generated. This generation of change implementation plans should be made simultaneously for all initiating changes to avoid conflicts during the implementation into the product. In reference to KRITIK method, which is described in section 3.4.2, a priority order for the initiating changes can be defined. Else, the planning order for the driving change requirements can be varied accordingly when no priority is specified.

On the other hand, it is known that CPM estimates the impacts of the proposed product modification through the product risk measurement used in risk management field. This scheme is well-recognized and hence it is applied for SPEC method as well. However, the identified issue with CPM is how the change likelihood and impact measures are derived from past change data. The analysis results by using such data might mislead the conclusion because the present change situation can be greatly different than those encountered in the past. Plus, in the presence of newly-available technologies, the current change impacts can be different for the same modification that is made in the past. To avoid such misleading circumstances, the SPEC methodology interacts with designers to determine those measures based SRL and cost rating scales. By doing so, the inputs into the analysis are more reflective of the present change task at hand.

Overall, the comparison of the change plan generation procedure in the proposed SPEC method and CPM is summarized in Table 76.

Table 76: Summarized Comparison of the Change Plan Generation Procedure

Required SPEC Characteristics	CPM	Change Plan Generation Step in SPEC	Remarks
Provide a structured redesign strategy	Predict the change effects propagation through any existing interconnections between the components without considering the change type or level	Derive the possible modification plans by varying the change roles of the aircraft components based on the defined change solution space. The change propagation is predicted through existing connections between the components, the change type and level	The consideration of the change type and level improves the accuracy of the change propagation prediction. In addition, the full exploration of the change solution space is made possible by varying the components' change role
Provide a proper redesign plan assessment scheme	Estimate the redesign risk as a product of the change likelihood and the change impact level, which are pre-defined in the model database	Estimate the redesign risk as a product of the change likelihood and the change impact level, which are interactively defined by the designers in real-time	The interaction with the designers allows a more representative definition of the measures that is reflecting the present change task at hand
Scalable to simultaneous initiating changes case	Does not support simultaneous change planning	Include the change priority definition or in cases when no priority is defined, the order is varied accordingly	The simultaneous planning is important to avoid any implementation conflicts and to allow full exploration of the change solution space

4.5 Chapter Summary

Based on the gained knowledge from the literature review that is presented in Chapter 3, several research hypotheses have been derived to help address the research questions. In addition, the literature study also highlights the absence of available methods or tools that fully capture the essences of aircraft redesign process. This supports the basic motivation for this research study that there currently exists an urgent need for a strategic redesign planning method that not only enables existing product designs to satisfy the new market requirements and demands, but also realizes them in the most efficient manner possible. Complete formulation of the proposed SPEC method has been explained in this chapter and while several available methods or tools have been used as the main references in its development, most of them are not directly applied within the method. Instead, some of their elements and underlying principles have been combined to resolve their identified deficiencies and improve their performance for application within the proposed method. This has been highlighted through the comparison of the formulated SPEC methodology with the referenced methods and tools.

In following Chapter 5, the anticipated capabilities from this proposed SPEC method are further demonstrated through two sample implementation case studies. The results from these studies are used to support the research hypotheses made in this chapter.

CHAPTER 5

IMPLEMENTATION OF PROPOSED METHODOLOGY

“*Organization’s efficiency can only be gained if its methods, techniques and process are aimed at serving competitive strategies for engineering change management*.”

- Riviere, DaCunha, Tollenaere (2002)

The proposed SPEC methodology has been thoroughly explained in preceding Chapter 4. In this chapter, two notional aircraft redesign studies are discussed to address the research questions and to verify the proposed research hypotheses. The main goal of these sample case studies is not to comprehensively design a derivative aircraft system but to highlight the capabilities of proposed redesign method with regards to outlined research questions and hypotheses.

For the first case study, the proposed methodology is applied to select a suitable baseline aircraft for a sample redesign task. To demonstrate the influence of design architecture in dictating suitability of a system to be adapted for its change requirements, three potential baseline candidates are evaluated against each other. Meanwhile, second implementation case study is aimed to demonstrate full range of formulated redesign planning procedures within the proposed SPEC method. In this example study, transparency of the decision-making process from initiating change requirements up to selection of the best redesign plan is shown through a notional aircraft system redesign scenario. For both case studies, the devised scenario for change requirements are tailored to more-electric aircraft (MEA) initiatives.

Before the sample case studies, first part of this chapter presents a general description of MEA initiatives that are considered as sample change requirements. The purpose for their explanation is to provide some insights on the type and level of system modification that should be expected from their implementation into an existing aircraft. This background knowledge is also useful for the following qualitative assessment of technology readiness and cost to be realized in aircraft subsystems.

5.1 More Electric Aircraft (MEA) Initiatives

In present aviation industry, there is an ongoing revolution by designers towards an all-electric aircraft (AEA) design. A study by Lockheed Corporation projected a savings of nine billion dollars over 16 years of AEA ownership for airlines in comparison to that of electrical-hydraulic-pneumatic-mechanical aircraft [95]. Note that this estimation is based on a fleet of 300 all-electric, 500-passenger aircraft. Although AEA remains a future goal within aircraft industry, several more-electric aircraft (MEA) ventures have already been initiated including those by US Air Force in the early 1990s [335]. This is perceived as a progressive step towards AEA with technologies to support an all electrically-operated aircraft are being developed step by step.

In general, the pursuit for AEA design aims to replace conventional aircraft accessories like high-pressure hydraulics, engine bleed air, pneumatics and non-electric engine-start systems with electric generators for a simpler and more reliable secondary power system [94, 99]. Instead of having subsystems powered by mechanical, hydraulic or pneumatic means, efforts are being made to have them all electrically-powered. This enables several value-added advantages in aircraft operation including reduction in subsystem weight and size, higher reliability and lower maintenance cost [49, 99]. The notion of future AEA is not entirely far-fetched since most modern aircraft systems are already designed with as much as 92% of electric/electronic operation [95]. Boeing B787 aircraft is Boeing's first MEA, which is equipped with ice and rain protection, landing gear, flight control, cabin pressurization and engine starting systems that are fully electrically-operated for the first time [49]. Cutts reported that although amount of research activities to advance electrical equipment and subsystems for aircraft application have notably increased in recent years, much of the efforts have been limited to a stand-alone demonstrator or simulation within existing electrical architectures [99].

For sample redesign case studies in this chapter, the focus is placed on MEA technologies that have been developed for flight controls, in-flight entertainment and electrical power distribution.

5.1.1 Electrical-based Flight Controls

In concert with MEA concept, there is a significant progression throughout the aerospace industry regarding fly-by-wire (FBW) system. Primary drivers behind this development are offered advantages of electronic flight controls against heavy maintenance-intensive hydraulic, pneumatic or mechanical systems [49]. Due to technological advancements in FBW field, electronic flight controls have become a standard in commercial and military aircraft system [53]. Available options for electrical actuation include electro-mechanical actuation (EMA) and electro-hydrostatic actuation (EHA). EMA uses an electric motor to directly drive actuator output through a mechanical gearing mechanism while EHA uses an electric motor to drive a dedicated hydraulic pump that provides hydraulic power for actuator output [99]. Though EHA reintroduces hydraulic elements in its operation, they are self-contained and do not involve the main aircraft hydraulic power subsystem. In the following sample case studies, the focus is put on EMA that is categorized under power-by-wire (PBW) approach. Thus far, it appears that electrical actuation systems are likely to require a 270V DC power supply. In the absence of a new electrical power generation and distribution scheme, power conversion units (PCUs) are installed to rectify existing three-phase, 115V AC power supply into 270V DC power [183]. Block diagram for PBW architecture of electromechanical actuator (EMA) is depicted in Figure 82.

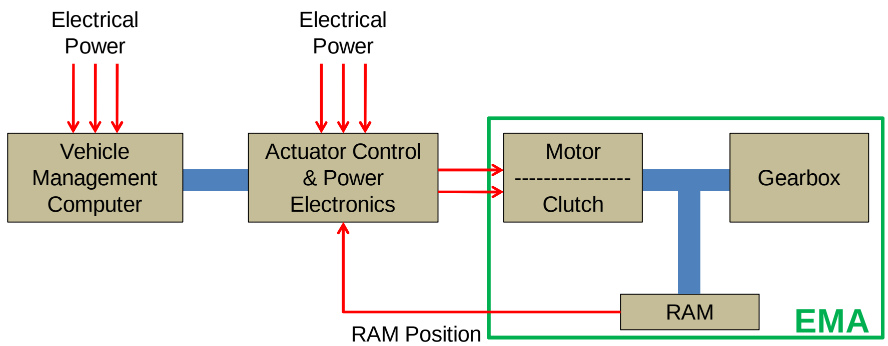


Figure 82: Basic Configuration for EMA Implementation [322]

In general, EMA consists of a servo-controlled, variable "speed and direction" electrical motor, a high-speed gearbox with gear reduction mechanism and a geared rotary actuator or a linear ballscrew [93]. For flight control application, primary elements of EMA are actuator module (AM) and electronic control unit (ECU). AM takes care of electrical-to-mechanical power conversion and mechanical transmission drive to control surfaces. In the meantime, ECU is responsible for EMA position control and loop closure, and control of its electric motor [93]. This is depicted in Figure 83.

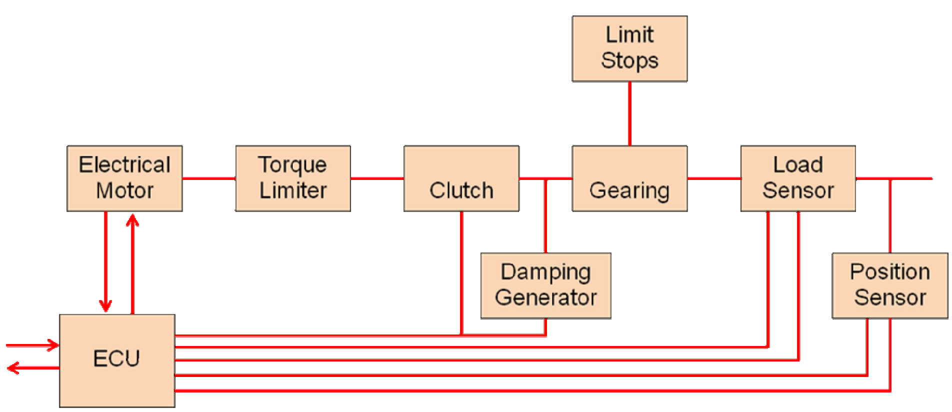


Figure 83: EMA Functional Diagram [93]

The maturity of PBW technology is lagging behind FBW. While its EMA configuration, electric motors and high-power electronic drives have been successfully demonstrated in test flights, their development has yet to be fully accepted within the aviation field [53]. An example illustration of the expected system integration for electrical power and flight controls subsystems in AEA concept is shown in Figure 84.

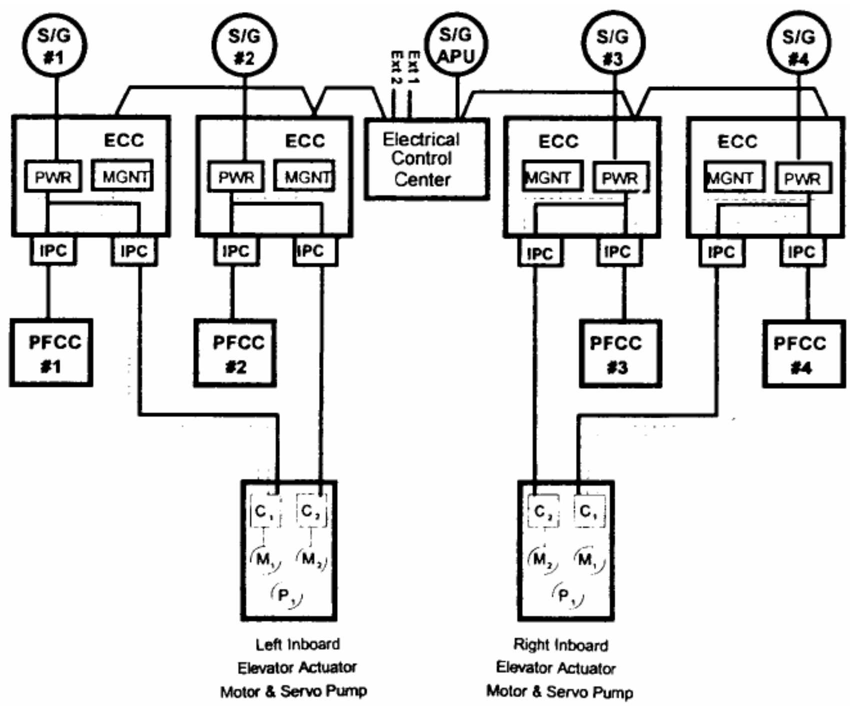


Figure 84: Integrated Electrical Power and Control of Elevator for AEA [132]

For system architecture in Figure 84, four control computers and electrical power buses are used to provide independent power and signaling for elevator actuators. Among the highlights of this expected architecture change are its features such as electrical actuator, intelligent power controller (IPC) and integrated power and signal cable. IPC exchanges and monitors load current data, which it then supplies to power management center and primary flight control computer (PFCC). Other flight control surfaces are also anticipated to be connected in a similar system architecture design and therefore, their actuation will benefit through cabling standardization [132]. Figure 84 also shows other system changes that might need to be made during implementation of EMA into an existing aircraft.

It can be concluded that EMA technology has already matured based on its application in many areas of aerospace designs, particularly missile design [93]. Moreover, it has been applied for secondary flight controls on commercial aircraft system but its application on primary flight controls has so far been limited to sample prototype demonstration due to safety concerns [93, 269]. Despite its potential to be the simplest and the most compact actuator, its operational reliability is a main issue for wider application. Recent research efforts are looking at several EMA design options for better load carrying, jam-resistant and fault tolerant capabilities [49].

5.1.2 Context-Aware In-Flight Entertainment System

Air traveling can cause some degrees of physiological and psychological discomfort, and subsequently introduce negative stress to aircraft passengers. Common means to relieve this situation during flight is by relaxing to movies or music that are available through in-flight entertainment (IFE) system [207]. IFE has become one of the competitive features to capture passengers market. It has been observed that airlines with a great service and favorable IFE features on their fleet often get the upper hand from passengers when they select their air travel options [198, 235]. This argument is echoed by Francois Quentin, senior vice president of Thales' aerospace, who said that IFE investment was among the first things that was considered by many airlines in their efforts to be more competitive when the aviation industry emerged from the downturn crisis of 2001-03 [317]. To date, progression of cabin IFE features is illustrated in Figure 85.

It can be noted that present in-flight entertainment systems are designed and implemented as an adaptive system, where entertainment services are personalized to user's selection [119]. For instance, many commercial airlines including Delta, Lufthansa, Air France and British Airways have their aircraft cabin furnished with a personalized entertainment unit at each passenger seat that allows individual selection of movie or music channels [206]. Though this cabin feature is designed for passengers' convenience to improve their flying experiences, some passengers still have problems to enjoy it due to poor interface design or limited choices that do not suit their personal preferences. In either case, IFE's primary function to reduce their negative stress is compromised and in some extreme situations, it can worsen the situation [207].

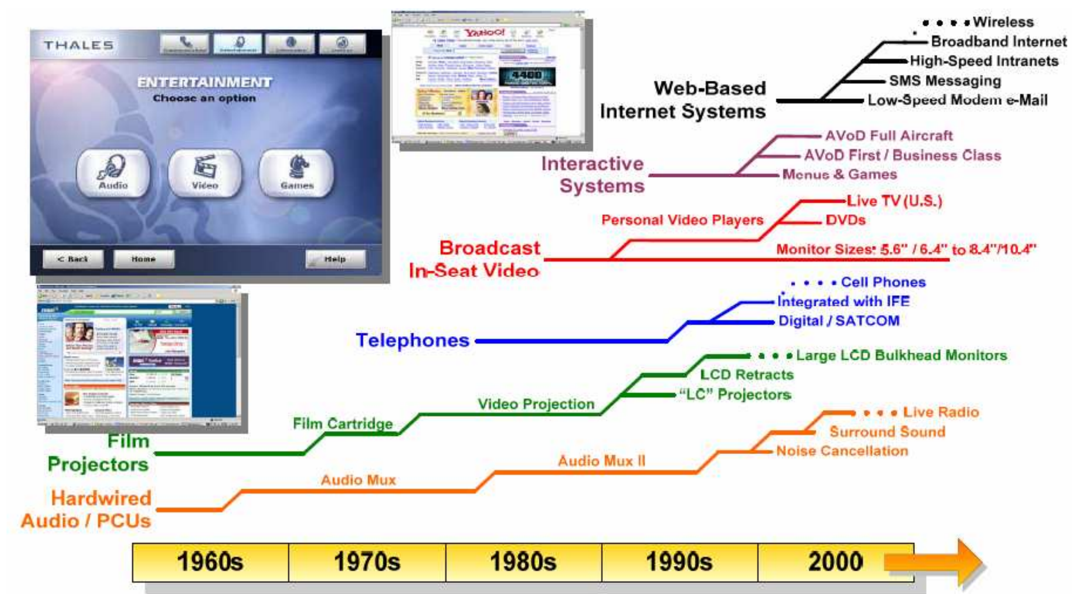


Figure 85: Technology Enablers for IFE [45]

To stay ahead of market competition, airlines have recognized the needs to improve their passengers' comfort level through their onboard cabin amenities, which is a key service differentiator for many air travelers [7]. This leads to exploration of how IFE system can be improved and one of the well-acknowledged ideas is to shift the system operational logic to context-adaptive.

During the 90's, the main paradigm for adaptive system is shifting from user-adaptive to context-adaptive. In this case, user's implicit requirements drive the system adaptation to facilitate them in getting their personalized services [101, 207]. Today, similar capability is proposed for IFE system to improve its functional efficiency with passengers. This is described as “Event-Control-Action” coordinated mechanism [208]. If a psychologically-stressed passenger is detected not doing anything substantial to cope with his stress level, IFE inference engine automatically plays a personalized “calming” music playlist that is based on his available information in the system database. To implement this operational logic, several changes have to be made to current IFE system architecture. The primary elements of this proposed context-aware IFE system are highlighted in Figure 86.

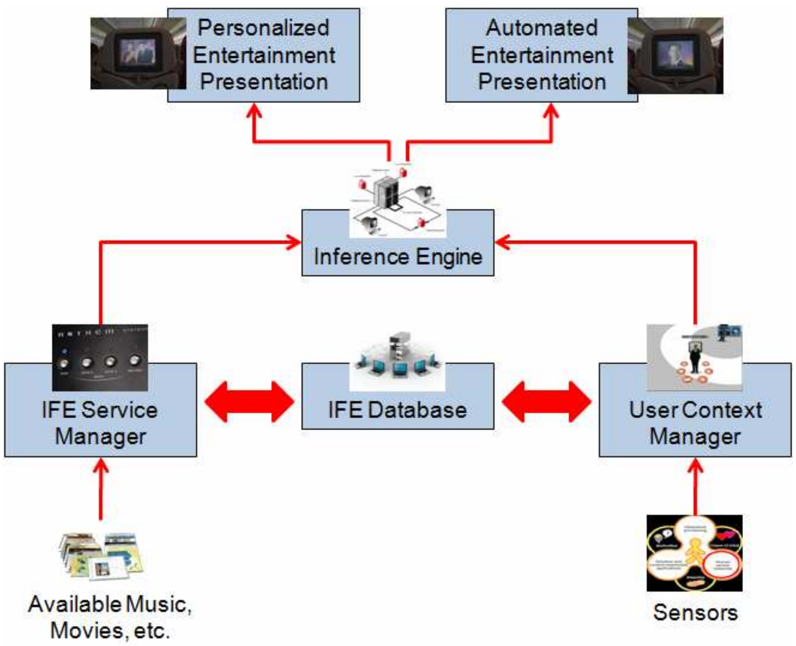


Figure 86: Architecture for Context-Aware In-Flight Entertainment System [208]

Main functions of entertainment service management unit are to register and categorize all available in-flight entertainment services. On the other hand, user-context manager is responsible to monitor passenger’s activity, physical and physiological states [208]. IFE database is updated with this information and combined with personal data collected from passengers prior to their flight such as their demographic background. Inference engine system moderates user-context management and entertainment services with intelligent selection stress-reducing entertainment options depending on physical and physiological state of individual passengers. Thus far, it has been reported that an experimental study on a passenger demonstrated potential improvements of his physical and psychological comfort through application of context-aware IFE system [208].

Provision of high-quality entertainment in aircraft cabin environment presents significant engineering challenges as passenger expectations can be very demanding and constraints of power, size, weight and maintainability imposed by aircraft design can be restrictive. For instance, individual flat panel display and input/output controls for each passenger in existing aircraft system designs have to consume no more than 25 watts [135]. For many advanced IFE concepts, electrical loads have been projected to approach nearly 100 watts per seat and future 600-seat Airbus A380 is expected to require 360kVa of total electrical power for passenger loads alone [235]. As suggested by Lee from Boeing Cabin Systems Enabling Technology, technologies behind many installed IFE equipment are usually not fully matured when they are implemented and this results in several last minute aircraft redesign efforts [198]. All in all, Figure 86 hints at some of the modifications that have to be made on current aircraft to implement context-aware IFE technology.

Thus far, literature references for this context-aware IFE technology seem to indicate that it is still predominantly in conceptual stage. While its implementation might benefit from matured technologies in other engineering fields like computing and electronics, it can be safely concluded that its implementation into an aircraft system has yet to be successfully demonstrated.

5.1.3 Advanced Electrical Power Generation and Networking

In general, many modern aircraft system designs employ subsystems that require either 115V AC or 28V DC supply for their operation. Consequently, different power electronic converters such as AC/DC rectifiers, DC/AC inverters and DC/DC choppers are required.

For MEA, the transition of more subsystems into electrical-based operation is expected to necessitate a multi-voltage level, hybrid DC and AC power supply network that should be able to convert one form of electrical power to the other and also its power level [124]. To successfully achieve MEA goals through electrical power generation and distribution system, several new technologies have been pursued including engine starter-generator and electrical power loads control and management [72].

Many aircraft systems currently generate their onboard electrical power supply using a machine/drive mechanism called constant speed drive (CSD) [122]. However, the future needs for various power types and increased loads are among the main challenges that this conventional mechanism has to face for MEA application. It is predicted that future electrical power demands will exceed 500kW per engine as a result of improved in-flight entertainment, information service and passenger comfort, and additional electrical load demands from major subsystems like flight controls and landing gear actuation [260]. In general, the projected electrical power demand increase is illustrated in Figure 87.

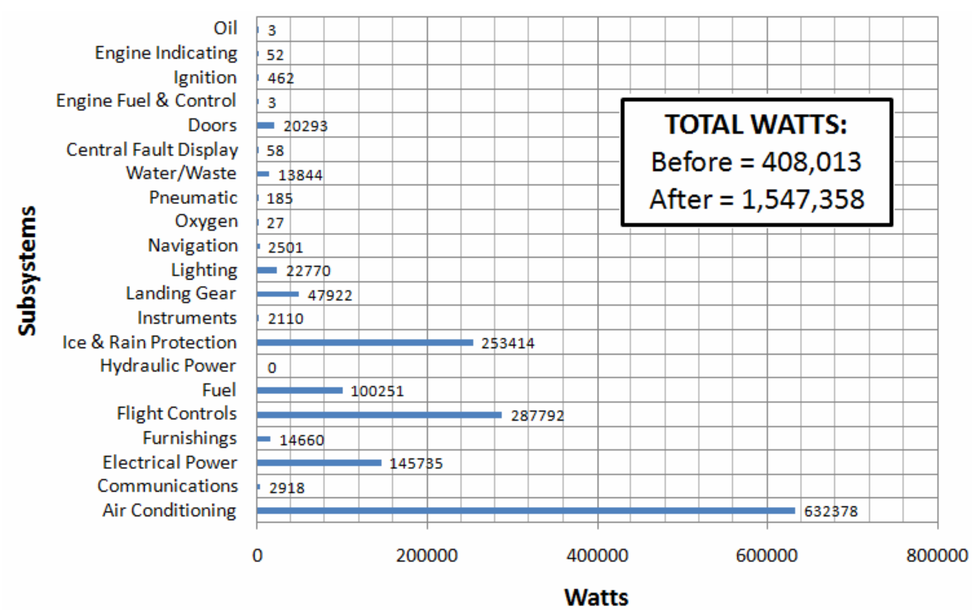


Figure 87: Estimates for Connected Electrical Loads in Future AEA [131]

Generator technology that is applied on existing commercial transport aircraft is a 3-stage wound-field synchronous generator that produces a constant-frequency 400Hz electrical power supply. In order to cope with varying engine speed, a variable-ratio transmission is needed between the engine and the generator. This transmission unit is expensive, heavy and inefficient, and affects the reliability of power generation mechanism [260]. In MEA initiatives, several power types that have been considered for electrical subsystem include constant-frequency 115V AC, variable-frequency 115V AC, variable-frequency 230V AC, 270V DC and hybrid architectures [99]. So far, experimental results indicates that the significant increase in electrical power demands for MEA may only be economically achieved by using reasonably high voltages AC and DC distribution schemes [183]. This realization leads to the implementation of variable-frequency 360-720Hz system such as on Bombardier Global Express and Airbus A380 aircraft [260]. The use of VSCF-based aircraft electric power systems offers the benefits of increased reliability, lower recurring costs and shorter mission cycle times in comparison to conventional CSDs [122].

With the notion of total hydraulic and pneumatic power systems elimination, another area that has a high development interest is the replacement of conventional engine air starter. In this case, engine starting mechanism is to be electrically executed by using the electric power generator as a motor [260]. With the advancements in power electronics, control electronics, electric motor drives and electric machines, VSCF electrical starter-generator technology emerges as the best replacement to conventional CSD and pneumatic engine starter mechanisms [124]. It is expected that a single channel of 180-kVA capacity will be required for engine starting [132] and a typical integration of VSCF starter-generator technology into an aircraft system is illustrated in Figure 88.

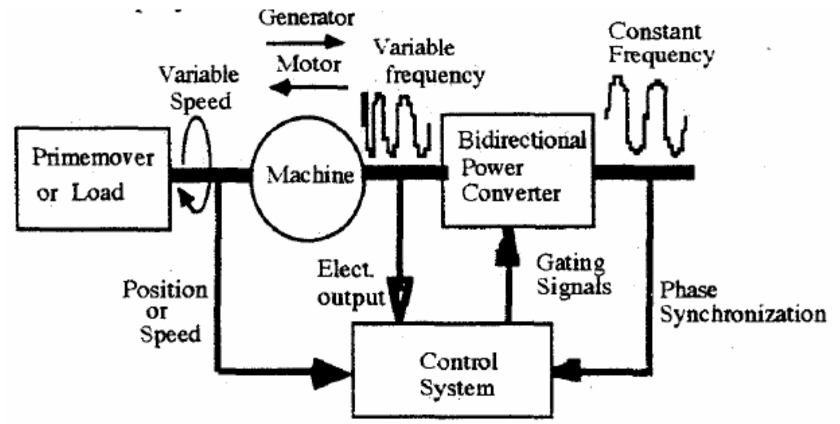


Figure 88: Typical VSCF Starter/Generator System [122]

In its motoring mode, a starter-generator provides power to aircraft engine but in reverse, it receives variable-speed load inputs from the engine during its generating mode. This mode switching is controlled by a designated controller unit. For most part, this VSCF technology has matured and already been used in several aircraft applications, although in a much smaller operational scale than expected in AEA [235]. There are some issues that need to be resolved before its full application in aircraft system, including a cooling scheme for starter-generator unit and changes to engine structure for its accommodation [260].

Once electrical power has been generated, it needs to be distributed to various onboard aircraft subsystems. Electrical power distribution within current aircraft system designs is accomplished without the need for power electronics [131]. For instance, simple on/off relays or switches have been used to control the operation of fans and pumps. However, the move towards AEA creates urgent needs for improvements in power electronics and their controls [269]. In Figure 89, a study on AEA design indicates a potential increase in variety of electrical load demands from future electrical-based aircraft subsystems, which then translates into an increase in required load distribution groupings.

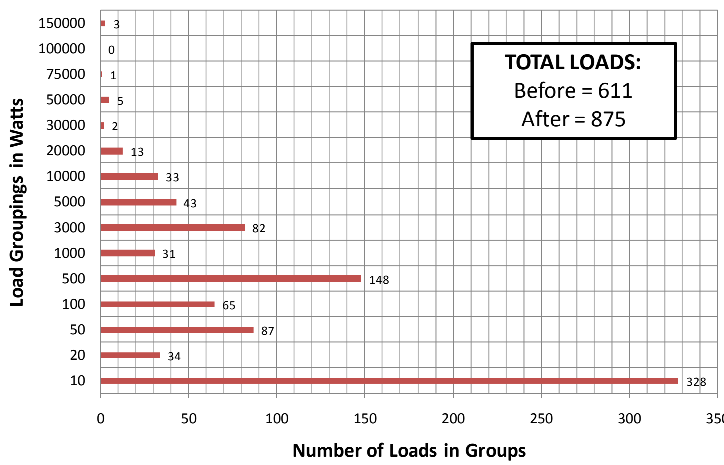


Figure 89: Estimated AC Bus Loads in Various Wattage Ranges for AEA [131]

Power electronics in AEA design architecture are responsible for three main tasks: on/off switching of electrical loads (which is accomplished by mechanical switches and relays in conventional aircraft designs), control of electric machines and conversion of electrical power supply [124]. To show different roles of power electronics, conceptually-advanced aircraft power system architecture is shown in Figure 90.

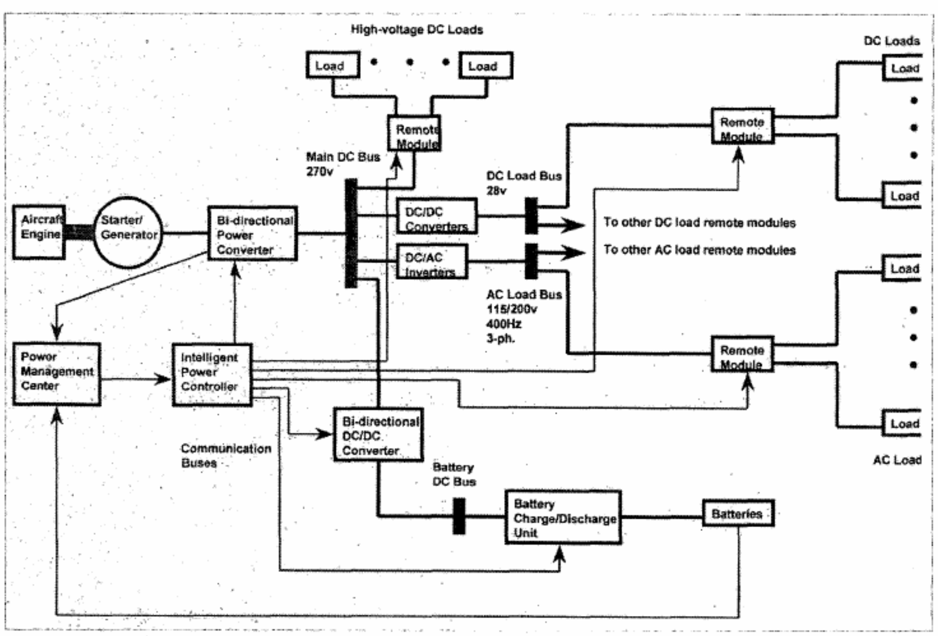


Figure 90: Conceptual Advanced Aircraft Power System Architecture [124]

In Figure 90, VSCF starter/generator system supplies variable frequency AC power to a bi-directional power converter unit, which converts it into AC constant frequency voltage for main electrical distribution bus. For this advanced electrical power architecture, the number and length of electrical wires are minimized by using intelligent remote modules to control the loads. Moreover, power management system (PMS) will take advantages of interconnections between remote modules to reduce peak power demand by time-phasing the duty-cycle of different loads. It also acts as an overall management unit for electrical power supply and starter/generator systems.

It is concluded based on available reference literatures that power electronics to support implementation of high-power electrical power aircraft subsystem is not fully matured as yet. Though several new technologies have been successfully demonstrated, such as solid state power electronics for converting high-level electrical power from variable frequency to constant frequency, several issues still need to be resolved before this advanced power architecture can be fully implemented into an aircraft [99]. Among others, these include concerns over the weight, size, electromagnetic interference and thermal management of power converters [260]. On a positive note, several new emerging technologies have been shown to be encouraging including improvements in capacitor technology and design of motors and controllers, which can eliminate the weight, size and reliability issues [122].

5.1.4 Summary of Considered MEA Initiatives

The current state of considered MEA technologies can be measured based on SRL scale, which is summarized in Table 77. This information can be used to assess redesign risks and impacts, and to evaluate baseline design adaptability and extensibility characteristics with regards to required changes. Individual assessment for components that are involved in implementation of these technologies can be made based on previous discussion.

Table 77: Summarized State of Considered MEA Technologies

MEA Technology	SRL Level	Main Literature References
Electro-Mechanical Actuator (EMA)	4	[37, 49, 93, 99, 269, 322]
VSFC High Power Starter-Generator	4	[123, 260]
Power Electronics for Advanced Electrical Networking	4	[49, 123, 124, 269]
Context-Aware IFE Systems	3	[198, 207, 208]

5.2 Case Study 1: Derivative Aircraft with Electrical Flight Controls

The focus of this experiment is to demonstrate the competency of SPEC method to assist aircraft designers in making their decision on baseline selection with respect to redesign suitability and risk, apart from the usual emphasis on proximity of existing capabilities to driving requirements. Outputs from this assessment can be used to reflect on whether the decision to redesign an existing aircraft system is justified against developing an original design altogether. As discussed before, if the development of derivative aircraft requires similar amount of costs and market lead times with that of original aircraft (for the same requirements), it will be hard to justify the redesign investment. In perspective, research questions and hypothesis that are directly addressed by this first experiment are depicted in Figure 91.

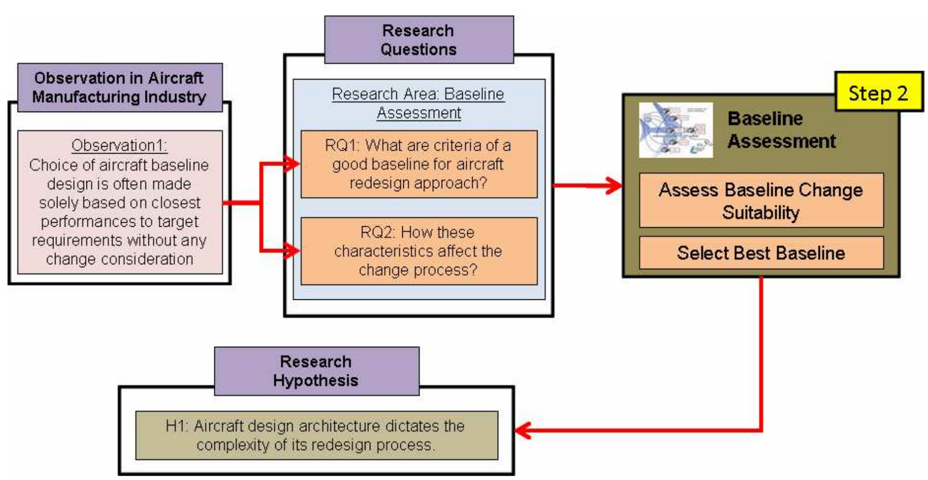


Figure 91: First Experiment – Influence of Baseline Architecture

One of the main differences between aircraft system designs that are available in current market is their flight control architecture. Though many aircraft can comparably perform similar flight missions, their subsystems are designed differently. In this example case study, three potential candidates are considered for the baseline design. As suggested in Chapter 2, the competitiveness of aircraft design from airlines' viewpoint is measured by its capacity and range [88, 266]. Taking this into account, change requirements for this sample redesign scenario are presented in Table 78.

Table 78: Driving Change Requirements for Case Study 1

Requirements	Target / Constraints	Baseline Candidate		
		Airbus A320 [1]	Lockheed L-1011 [9]	Boeing B727-100 [3]
Flight Range	>= 3900 nmi	3000 nmi	4003 nmi	2700 nmi
Maximum Capacity	>= 234	180	263	149
Gross Weight	<= 255,000 lb	169,000 lb	466,000 lb	169,000 lb

As indicated in Table 78, the considered baseline candidates are Airbus A320, Lockheed L-1011 and Boeing B727-100 aircraft. The settings for driving change requirements are made in reference to Boeing B757-200 [5], which ensures that they are reasonable to be achieved in real practices. To date, the tendency is to choose a baseline design based on the closeness of its performances to the driving requirements. To illustrate this approach, consider the application of Pugh Evaluation Matrix in Table 79. For information, this is a simple but well-recognized multi-criteria decision-making method that aids the selection of the best alternative with respect to established datum point. In this case, the datum for each performance requirement is taken from their formulated target value.

Table 79: Pugh Performance Evaluation Matrix of Baseline Candidates

Requirements	Datum	Baseline Candidate		
		Airbus A320	Lockheed L-1011	Boeing B727-100
Flight Range	>= 3900 nmi	-	+	-
Maximum Capacity	>= 234	-	+	-
Gross Weight	<= 255,000 lb	+	-	+
TOTAL		1+, 2-	2+, 1-	1+, 2-

If based on this simple qualitative assessment, Lockheed L-1011 aircraft appears to be a slightly better baseline candidate for this redesign task than either Airbus A320 or Boeing B727-100. However, it can also be implied that all of them require some modifications that can potentially affect their performances if chosen as the baseline. Lockheed L-1011 aircraft will most likely require the scaling down of its existing system design to improve on its gross weight performance. In contrast, the expected expansion of their design to accommodate more passengers and onboard fuel to extend their flight range will increase the weight of both Airbus A320 and Boeing B727-100 aircraft, perhaps over the limit. In general, two main questions that remain after such typical high-level system performance assessment for baseline selection are listed as follow:

1. Which modification will be more difficult and risky to be executed?
2. How existing performances will be affected by the required system changes?

These are the main deficiencies of present approach that are targeted to be improved by the baseline assessment procedure within the proposed SPEC method.

Based on the formulated change requirements, this section will describe in detail how the proposed SPEC method can be applied to select the best baseline for impending aircraft redesign development process or to assess whether the redesign risks of selected baseline is manageable for the process to be pursued. The first part of this section illustrates how aircraft change models are created based on the taxonomy of system elements interaction proposed by Pimmler and Eppinger [257]. Next, using these system models, the baseline assessment process is executed to identify and select the best one among the considered candidates. In order to control the problem size for a more transparent demonstration of this baseline assessment procedure, it is assumed that expected gross weight problems for each baseline candidate (if they were eventually chosen to be the baseline) will be coped with EMA implementation in their primary roll control mechanism. While there might be other necessary changes depending on their system architecture, this narrowed scope is perceived as adequate to demonstrate the full capacity of baseline assessment procedure in the proposed SPEC method. It should also be noted that it is highly possible for the proposed design changes on each baseline candidate to be different from each other since they correspond to different levels of performance deficiencies to the target requirements. For the proposed EMA implementation in this sample case study, none of the candidate aircraft designs was originally equipped with such technology and their roll control was accomplished using hydraulically-operated actuators [338].

5.2.1 Creation of Change Models

To identify initiating change components, each baseline candidate has to be appropriately modeled. Since the problem scope has been narrowed down to only redesign changes in primary roll control mechanism, the construction of change model for this first case study can be focused on aileron control. The models are developed based on available reference literatures and their full discussion is presented in Appendix A. In summary, all processes involved in the change model construction for primary roll control mechanism in baseline candidates are listed as follow:

1. Identify baseline aircraft candidates
2. Search available reference literatures subsystems description for each candidate
3. Decompose baseline candidates based on their physical system description

4. Construct DSM change model for each candidate based on their physical system decomposition according to taxonomy of system element interactions

The DSM model for each baseline candidate is presented in following Figure 92, Figure 93 and Figure 94.

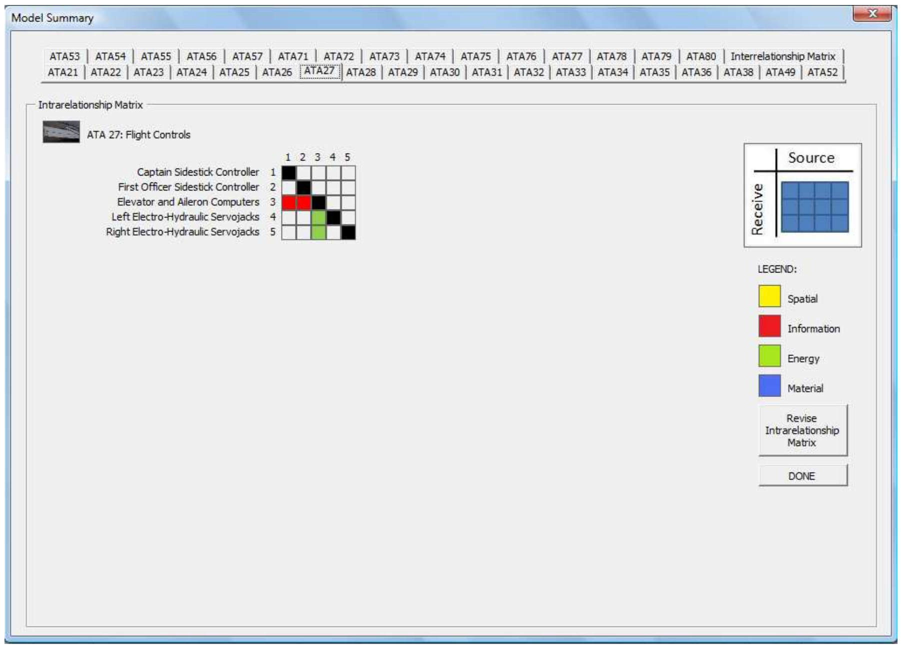


Figure 92: DSM Change Model for Primary Roll Control of Airbus A320

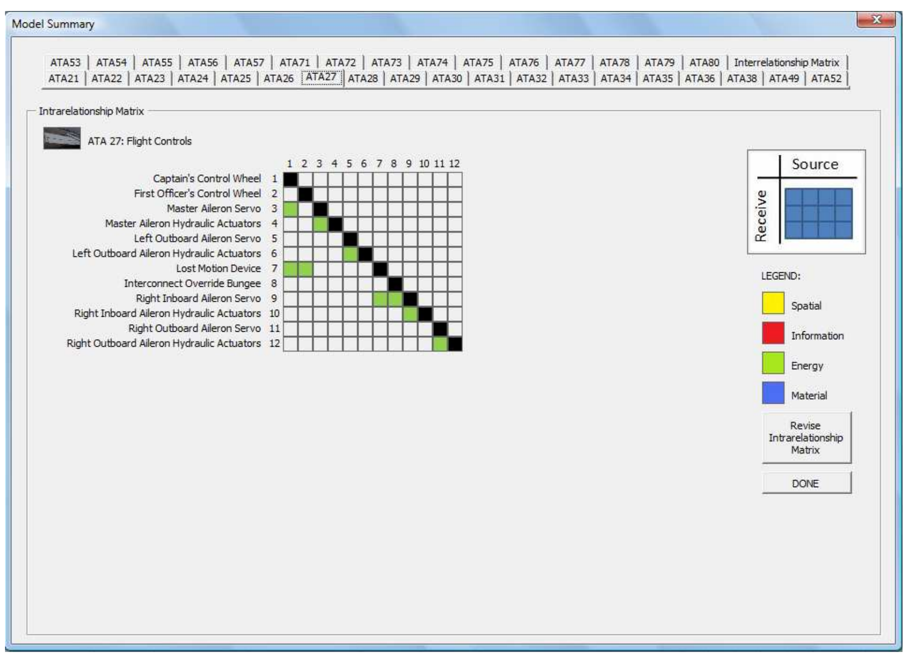


Figure 93: DSM Change Model for Primary Roll Control of Lockheed L-1011

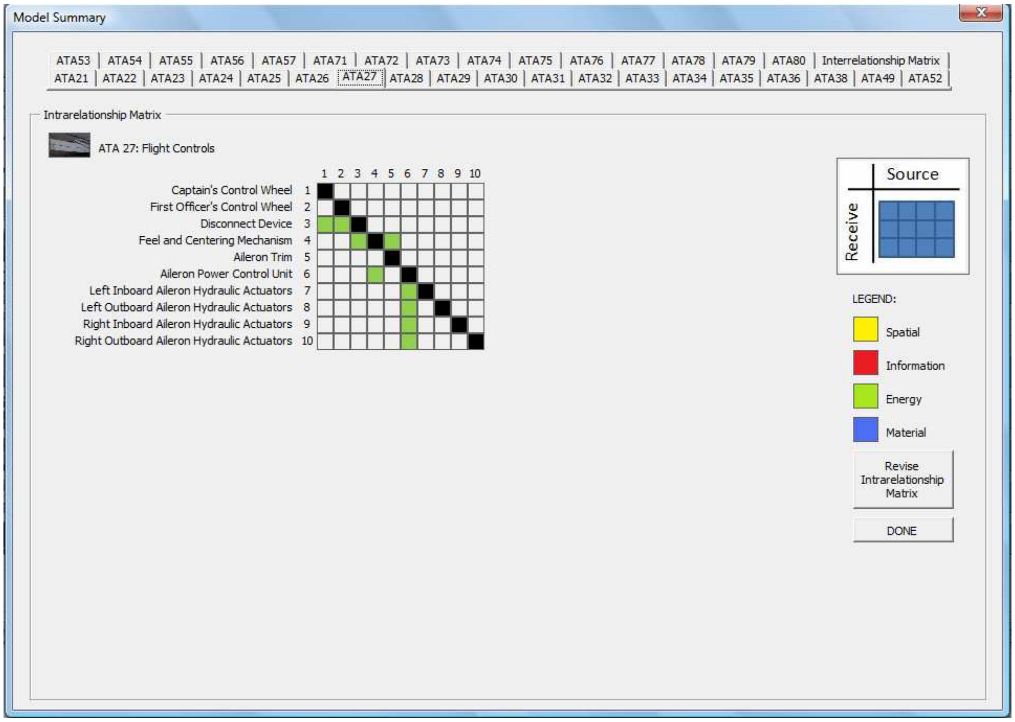


Figure 94: DSM Change Model for Primary Roll Control of Boeing B727

5.2.2 Assessment of Baseline Candidates

It should be emphasized again that main objectives of this procedure are to aid designers in selecting the best baseline for their redesign approach and in evaluating whether their associated redesign risks is reasonable to further pursue the derivative development.

Recall conceptual electrical-based flight controls architecture depicted in Figure 84 and discussion of its related technologies back in section 5.1. This is taken to be the eventual primary roll control system architecture that results from EMA implementation. Based on this, initiating change components for each baseline candidate can be identified and they are listed in Table 80. These components are directly affected by EMA implementation, either through replacement with a new unit or installation of additional unit to match the operational requirements of the new system architecture.

Table 80: Identified Initiating Change Components

Baseline Candidates	Initiating Change Components
Airbus A320	Left Electro-Hydraulic Servojacks Right Electro-Hydraulic Servojacks
Lockheed L-1011	Master Aileron Hydraulic Actuators Left Outboard Aileron Hydraulic Actuators Right Inboard Hydraulic Actuators Right Outboard Hydraulic Actuators Master Aileron Servo Left Outboard Aileron Servo Right Inboard Aileron Servo Right Outboard Aileron Servo
Boeing B727	Left Inboard Aileron Hydraulic Actuators Left Outboard Aileron Hydraulic Actuators Right Inboard Hydraulic Actuators Right Outboard Hydraulic Actuators Aileron Power Control Unit

Based on aileron control schematics presented in Appendix A, it is clear that mechanical-based control systems on Lockheed L-1011 and Boeing B727 aircraft are relatively more complex than electrical-based control on Airbus A320 aircraft. This situation is reflected by the number of initiating change components in Table 80. EMA implementation has the least impact on A320 aircraft since its flight control is mostly electrical-based. Its only major change is to replace its existing electro-hydraulic servojacks with EMA actuators. On contrary, mechanical-based flight roll control on Lockheed L-1011 aircraft is the most affected by the proposed change. In addition to hydraulic actuators, its mechanical servo units also have to be replaced with those that are electrical-based. Similarly, hydraulic actuators and mechanical-based aileron power control unit on Boeing B727 aircraft also need to be replaced. It is noted that the number of aileron surfaces also contributes to the required redesign efforts; favoring Airbus A320 aircraft design that only has two ailerons in comparison to four for Lockheed L-1011 and Boeing B727 aircraft.

Once all initiating change components are identified, the following step is to evaluate the redesign risks that are associated with their modification. Generality and scalability risk assessments can be made based on the candidate's performance characteristics as listed in Table 78. The risk scores are tabulated in Table 81.

Table 81: Generality and Scalability Scores for Case Study 1

Requirements	Airbus A320		Lockheed L-1011		Boeing B727	
	Generality	Scalability	Generality	Scalability	Generality	Scalability
Flight Range	100	0	0	0	100	0
Maximum Capacity	100	0	0	0	100	0
Takeoff Gross Weight	0	0	100	0	0	0
TOTAL	200	0	100	0	200	0
Normalized Score	2/3 = 0.67	0	1/3 = 0.33	0	2/3 = 0.67	0

With regards to Table 81, Lockheed L-1011 appears to be a better candidate based on the proximity of its existing performances to the driving requirements compared to the other two candidates. It can be implied that the assessment of these two redesign risk metrics is reminiscence of typical baseline selection approach based on proximity of performance characteristics to target requirements. Although it is known at this point that the primary roll control mechanism on all candidates is not equipped with EMA implementation, it is hard to identify which one is better suit for the redesign approach from that perspective based on high system-level information in Table 81. One might ask if Lockheed L-1011 is really the best baseline candidate since it has the highest number of initiating change components for its EMA implementation. In similar fashion, despite the fact that Airbus A320 and Boeing B727 aircraft have the same generality and scalability risk scores, do they correspond to similar level of redesign risks? In the proposed SPEC method, these aspects are captured using extensibility, adaptability and complexity system evolvability metrics. The following assignment of change impact and cost measures is made based on the description in previous section 5.1.

Table 82 lists the adaptability and extensibility risks for Airbus A320 primary roll control in relation to EMA implementation. Assessment of adaptability risk is based on whether the change effects due to installation of the electrical-based actuators can be contained without affecting other components. In Airbus A320 design, this containment is possible if the EMA can operate with similar amount of electrical power that is presently passed to its servojacks. Based on previous description of EMA, its development is focused on a 270V DC power supply that is not a common attribute of present aircraft electrical power system. This implies that the current power supply is lower than that expected for EMA and hence the adaptability risk here relates to the possibility that EMA can be made to perform with a lower power supply. Since current EMA development is taken to be at SRL level 4 in previous Table 77, this additional operational constraint on its application is assumed to be at lower maturity of SRL level 3. SRL level for current development of EMA is considered for extensibility assessment. In addition, measure of change cost is assigned according to the predicted extent that the manufacturing process will have to be changed to accommodate the implementation of proposed design changes. For the Airbus A320 manufacturing process, the cost is not expected to differ much because its current design is already highly electrical-based.

Table 82: Adaptability and Extensibility Risk Assessment for Airbus A320

Proposed Redesign Changes	Initiating Change Component	Change Remarks	Adaptability Assessment		Extensibility Assessment	
			Impact	Cost	Impact	Cost
EMA Primary Roll Control Mechanism	Left Electro-Hydraulic Servojacks	Changed to EMA	6	4	4	4
	Right Electro-Hydraulic Servojacks	Changed to EMA	6	4	4	4
		TOTAL	48		32	

With similar arguments, Table 83 and Table 84 list the adaptability and extensibility risks assessment for Lockheed L-1011 and Boeing B727 aircraft candidates, respectively, with regards to EMA implementation. Adaptability risk scores for both Lockheed L-1011 and Boeing B727 aircraft are given the maximum 100 for each initiating change component. This reflects the relatively high inflexibility of mechanical-based control scheme onboard these two aircraft with respect to proposed changes. For instance, in order for the existing aileron servo to contain the change effects within its architecture locality, its modification needs to include a mechanism that can convert incoming mechanical control inputs into electrical inputs for the EMAs. It is highly infeasible to realize this without affecting the electrical power system and their assigned adaptability risk scores reflect this condition. On the other hand, reasons behind their extensibility assessment are mostly similar to that explained for Airbus A320.

Table 83: Adaptability and Extensibility Risk Assessment for Lockheed L-1011

Proposed Redesign Changes	Initiating Change Component	Change Remarks	Adaptability Assessment		Extensibility Assessment	
			Impact	Cost	Impact	Cost
EMA Primary Roll Control Mechanism	Master Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Left Outboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Right Inboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Right Outboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Master Outboard Aileron Servo	Changed to electrical	10	10	1	4
	Left Outboard Aileron Servo	Changed to electrical	10	10	1	4
	Right Outboard Aileron Servo	Changed to electrical	10	10	1	4
	Right Inboard Aileron Servo	Changed to electrical	10	10	1	4
		TOTAL	800		112	

Table 84: Adaptability and Extensibility Risk Assessment for Boeing B727

Proposed Redesign Changes	Initiating Change Component	Change Remarks	Adaptability Assessment		Extensibility Assessment	
			Impact	Cost	Impact	Cost
EMA Primary Roll Control Mechanism	Left Inboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Left Outboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Right Inboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Right Outboard Aileron Hydraulic Actuators	Changed to EMA	10	10	4	6
	Aileron Power Control Unit	Changed to electrical	10	10	1	4
		TOTAL	500		100	

In terms of complexity assessment, replacement of parts and interfaces associated with initiating change components is expected to be made in a one-to-one condition. Each of hydraulic-based actuators is replaced with an electrical-based actuator and new electrical interfaces requirement is cancelled out by the elimination of hydraulic power lines to the actuation control unit. Thus no significant change in design complexity is anticipated for the baseline candidates. Nonetheless, according to previously constructed system models, roll control system for Lockheed L-1011 aircraft is perceptively the most complex among the candidates. Hence the normalization of complexity metric will be made in reference to its total amount of parts and interfaces. In real aircraft assessment study, total number of parts and interfaces refers to the overall aircraft system but in this case, it is referenced only to the primary roll control system due to lack of data to construct a complete aircraft model for each candidate.

To highlight the execution of this baseline assessment procedure using the SPEC support tool, the program snapshot that depicts measurement inputs for Lockheed L-1011 aircraft (as previously tabulated in Table 81 and Table 83) is shown in Figure 95.

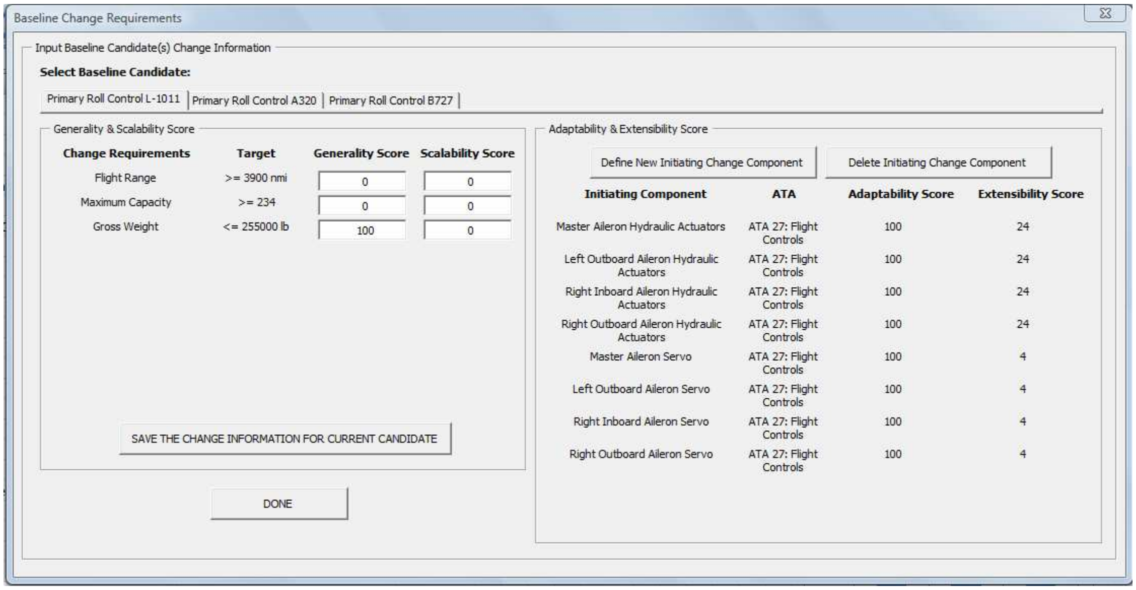


Figure 95: SPEC Program Snapshot of Baseline Assessment Input Interface

Individual comparison of system evolvability metrics for baseline candidates is presented in Figure 96. As discussed before, if the baseline assessment process is solely based on generality and scalability risks, Lockheed L-1011 appears to be the best candidate since its present capabilities satisfies two out of three formulated requirements. In comparison, both Airbus A320 and Boeing B727 only satisfy one target requirement. This situation is reminiscence to the practice of baseline selection based on proximity of its performances to the requirements. When risks regarding adaptability and extensibility redesign efforts are evaluated, they highlight a different story. From Figure 96, Airbus A320 visibly has the best adaptability and extensibility risk scores that imply its proposed redesign changes are easier to be implemented than for other candidates. In addition, derivative design for A320 is perceptively less complex than that of the others, which is favorable in terms of minimizing risks of change effects propagation [115]. If an equal importance weighting is assigned to these system evolvability metrics, the overall evolvability risk score for the baseline candidates is shown in Figure 97.

Figure 96: Comparisons of System Evolvability Metrics

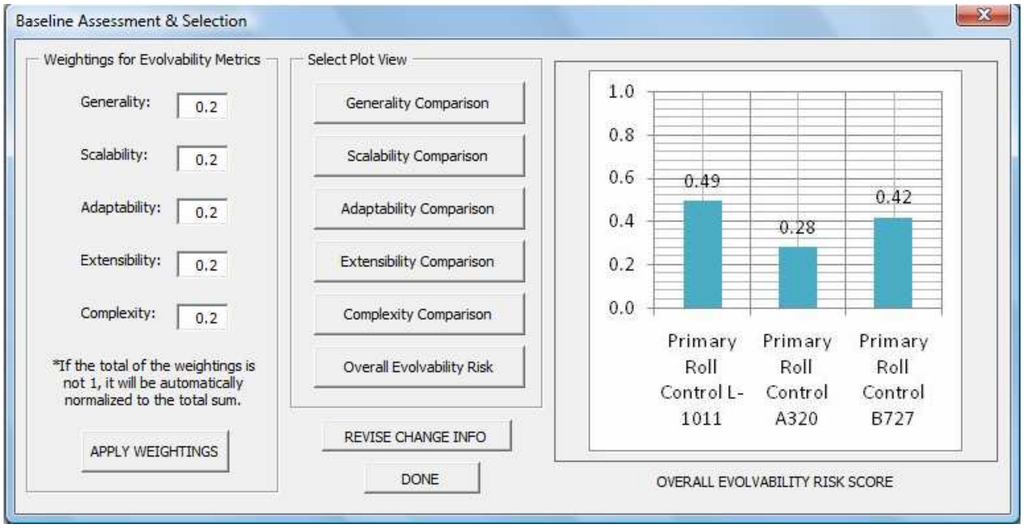


Figure 97: SPEC Program Snapshot of Baseline Assessment Results

The overall system evolvability risk score is a combined assessment of performance and redesign process difficulty, which reflects more on the aptness of baseline aircraft for its derivative development than just the closeness of its performance characteristics to target requirements. For this particular weighting scenario, Airbus A320 clearly emerges as the best candidate. Though its current high-level system performances are mostly in violation of the driving requirements, it is concluded from this result that design changes to resolve them are relatively easier to make than those for other candidates. In contrast, despite the closeness of Lockheed L-1011 performances to the requirements, its redesign process is much more difficult and riskier than the others.

To demonstrate a different weighting scenario, consider a case when manufacturer puts a high emphasis on having the smallest amount of affected components. This condition can be translated into a higher weighting for adaptability risk score, which corresponds to the difficulty in containing the change effects only within initiating change components. In addition, a higher weighting for generality risk can also be considered as fewer violated requirements often indirectly suggest less conflicts to be resolved. In this case scenario, weights for adaptability and generality risk metrics are respectively assigned as 0.5 and

0.2 while other aircraft system evolvability metrics are equally assigned with a weighting of 0.1. Baseline assessment results for this redesign scenario are presented in Figure 98.

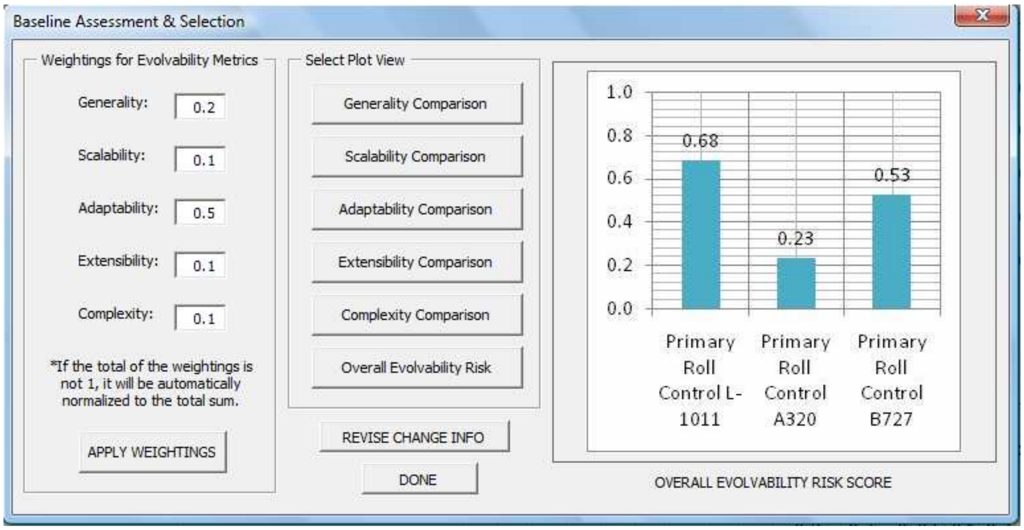


Figure 98: Baseline Assessment Results for Modified Weighting Scenario

As should be expected, the difference of overall evolvability risk score for Airbus A320 to other baseline candidates becomes more pronounced for this weighting case scenario. This condition is primarily because its number of initiating change components is much smaller than other candidates, which is exactly the main objective behind this weighting scenario. In addition, adaptability risks associated with their modifications are relatively lower than for other candidates.

5.2.3 Conclusion from Case Study 1

This first implementation case study is concentrated mainly on one main research area of the proposed SPEC methodology, which is baseline assessment procedure. Due to limited availability of full subsystems design information in public domain, it is hard to create an accurate representation of existing aircraft designs. For that reason, this study is narrowed down to redesign comparison of primary roll control system in three aircraft candidates: Airbus A320, Boeing B727 and Lockheed L-1011.

Referring to Figure 91, hypothesis 1 suggests that redesign process complexity is dictated by the characteristics of aircraft architecture. This conception is generally in conflict with common approach in baseline selection, which favors candidates with close performance capabilities to the driving change requirements since this condition is assumed to assure minimum and less risky redesign efforts. As demonstrated with a simple Pugh Evaluation Matrix procedure, Lockheed L-1011 is probably chosen as the baseline according to such notion. However, it is highlighted by results from this case study that such proposition is not always true because the flexibility of its design architecture also dictates how difficult it is to alter the baseline. For instance, roll control architecture onboard Lockheed L-1011 is relatively complicated and inflexible to accommodate the proposed realization of EMA technology. While sometimes it is true that fewer change requirements might induce less required changes, inflexibility of baseline design can still make the modification process very costly and risky even with minimum changes. Thus the measure of redesign process complexity based only on amount of required system modifications is indeed misleading and this will be further addressed by second case study.

As indicated by the baseline assessment results, Airbus A320 is evaluated as the overall best candidate with respect to formulated redesign scenario. While its current capabilities are a little short from the governing requirements in comparison to other candidates, its design architecture is more flexible to cope with proposed initiating changes to resolve its performance deficiencies. A different conclusion could be derived for the same group of candidates in different redesign circumstances, which implies that this result is scenario-based. For instance, instead of EMA technology incorporation, the weight savings could be accomplished through installation of a better power-to-weight-ratio propulsion system and this redesign scenario might result in a different best baseline candidate. Required system design changes for each baseline to resolve their performance deficiencies to the same target requirements can also be different from each other.

To summarize, overall system evolvability risk metric in this baseline assessment can be viewed as a compromised balance between typical baseline selection approach and high influence of design complexity on redesign process risk. Coming back to hypothesis 1, it can be observed in Appendix A that primary flight roll control system architecture on the baseline candidates is of different complexity level to each other. Lockheed L-1011 has the most complex control architecture and consequently has the highest level of redesign risks associated with EMA implementation. In contrast, for the same EMA requirements, Airbus A320 design has the lowest level of redesign risks since its control architecture is the least complex among the candidates. Overall, this result supports the proposition of hypothesis 1 that redesign process complexity is influenced by system design architecture characteristics.

5.3 Case Study 2: Notional Aircraft Redesign for MEA

The main goal of this second implementation case study is to demonstrate the full range of proposed SPEC methodology in supporting aircraft designers in their decision-making process during early redesign. In this case, a complete notional aircraft model is subjected to more than one design change, which is a common scenario in aircraft manufacturing. In real practice, this whole process involves several subsystem design teams. This second case study is also intended to address the research hypotheses in previous Chapter 4.

For this case study, it is assumed that the designers have decided from their requirements analysis process to implement EMA and context-aware IFE technologies into the notional aircraft. These change requirements can induce conflicting change effects propagation to other components in the aircraft system architecture. This condition provides the perfect setting to test the applicability of proposed SPEC method in aircraft redesign process.

5.3.1 Step 1: Aircraft Change Modeling

The first step is to model existing design architecture of the notional aircraft. If more than one baseline candidate is being considered, their corresponding change model should be constructed. However, only one notional aircraft system is considered in this second case study. The notional aircraft model is constructed from available subsystems description in public literatures and the summary of these references is presented in Table 85. A more detailed presentation of the DSM model for each subsystem is presented in Appendix B and their overall interrelationship matrix is shown in Figure 99. Spatial interrelationships between airframe and structural subsystems of the notional aircraft system are projected from Boeing B737 aircraft design cutaways diagram shown in Figure 100.

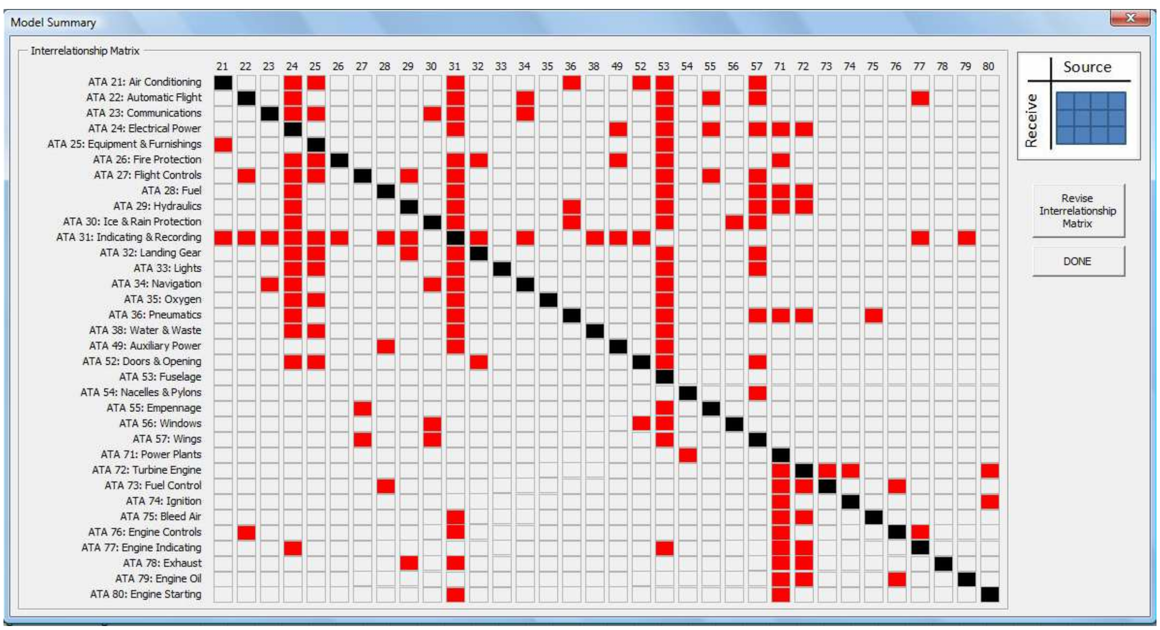


Figure 99: Notional Aircraft Subsystem Interrelationships

Table 85: Summary of Notional Aircraft Subsystems Model Build-Up

ATA Chapter	General Aircraft System Reference	Main Reference Literatures
ATA 21: Air Conditioning	B737	[17], [22], [42], [51], [55], [140], [180], [213], [225], [236], [338]
ATA 22: Automatic Flight	B737	
ATA 23: Communications	B757/B737	
ATA 24: Electrical Power	B737	
ATA 25: Equipment & Furnishings	General	
ATA 26: Fire Protection	B737	
ATA 27: Flight Controls	B727/B737	
ATA 28: Fuel	B737	
ATA 29: Hydraulics	B737	
ATA 30: Ice & Rain Protection	B757	
ATA 31: Indicating & Recording	B737	
ATA 32: Landing Gear	B757	
ATA 33: Lights	B757/B737	
ATA 34: Navigation	B757/B737	
ATA 35: Oxygen	B737	
ATA 36: Pneumatic	B737	
ATA 38: Water & Waste	L-1011/B757	
ATA 49: Auxiliary Power Unit	General	
ATA 52: Doors & Openings	B737	
ATA 53: Fuselage	B737	
ATA 54: Nacelles – Pylons	B737	
ATA 55: Stabilizers – Tail Units	B737	
ATA 56: Windows	B737	
ATA 57: Wings	B737	
ATA 71: Power Plants	General	
ATA 72: Turbine Engine	General	
ATA 73: Fuel Control	General	
ATA 74: Ignition	General	
ATA 75: Bleed Air	General	
ATA 76: Engine Controls	General	
ATA 77: Engine Indicating	General	
ATA 78: Exhaust	General	
ATA 79: Engine Oil	General	
ATA 80: Engine Starting	General	

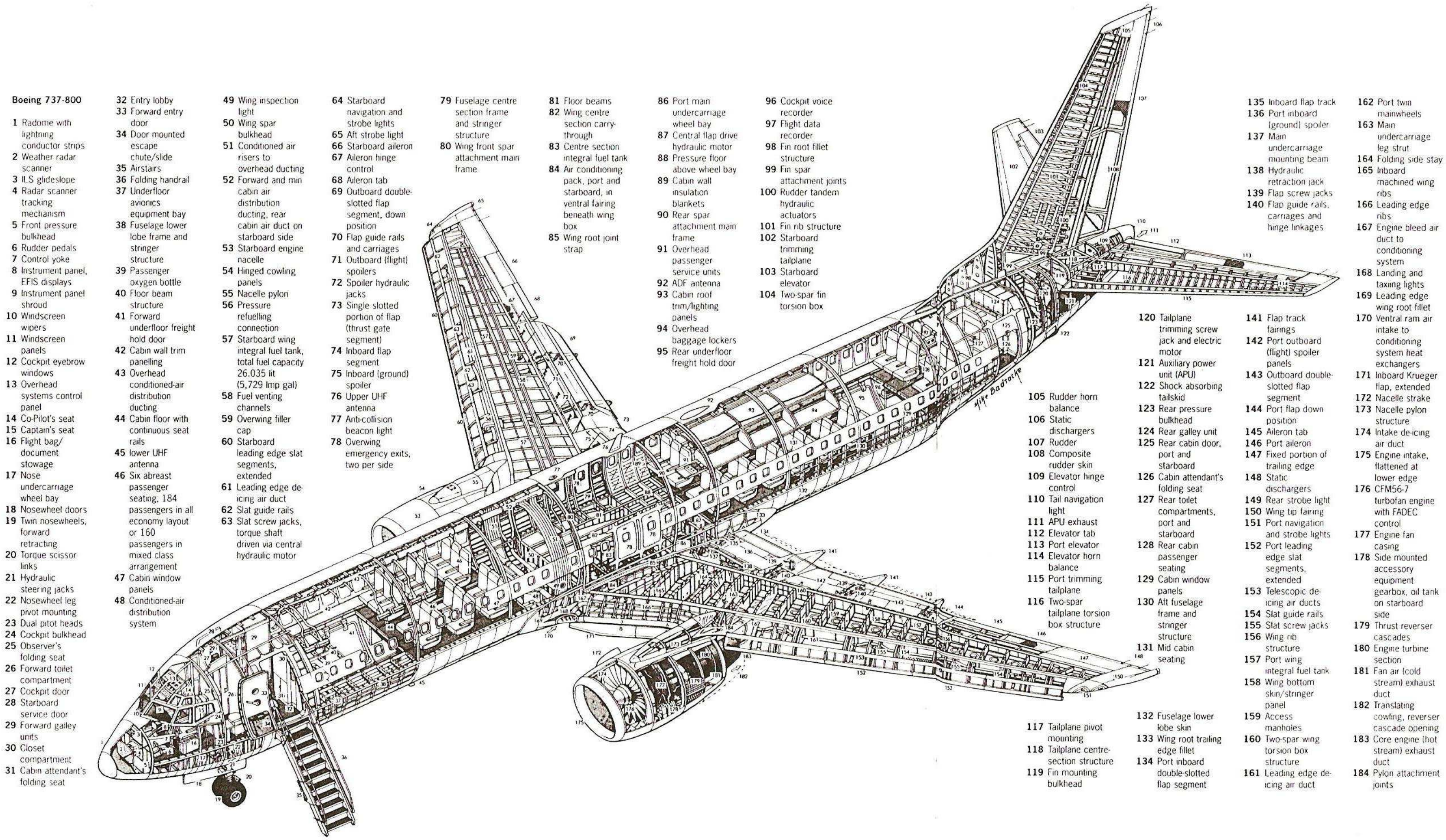


Figure 100: Boeing 737-800 Aircraft Design Cutaways Diagram [42]

5.3.2 Step 2: Baseline Assessment

It is of high interest to explore suitability of the notional aircraft to undergo the proposed redesign changes. As can be implied from Table 85 and Figure 100, the notional aircraft model for this sample case is mostly tailored to variants of Boeing B737 aircraft design. Therefore, it is fair to assume that the notional aircraft system has similar performance characteristics to Boeing B737. This assumption is considered while setting up plausible redesign scenario for this second example case study.

One of the main market factors that contribute to the prominence of derivative designs in aircraft industry is its high market competition. An example of a highly contested market segment is reflected in the competition between Airbus A320 aircraft family and Boeing B737 aircraft series. In July 2008, Bombardier joined the competition with their C-series aircraft line [149]. If the past trend of market competition between Airbus and Boeing is an indication of future aircraft offerings in this particular market segment, the increased competition level will introduce more derivative aircraft. As the notional aircraft system is argued to be closest to Boeing B737, the development perspective for this second case study will adopt that of its manufacturer.

General comparison of characteristics between competing aircraft models for this market segment is presented in Table 86. As discussed in Chapter 2, range and capacity are two important assessment criteria considered by airlines in their aircraft purchases [88, 266]. Based on Table 86, although passenger capacity and range characteristics of the notional aircraft are competitively similar to its competition, its gross weight is perceptively much higher. This condition seems to imply that the present notional aircraft system performs its flight mission with lower operational efficiency. Despite having comparable passenger capacity and a shorter flight range, its gross weight is much higher than the other aircraft designs.

Table 86: Comparison of Competing Aircraft Characteristics

Characteristics	A320 [1]	C130-ER [6]	Notional Aircraft*
Passenger Capacity	180	149	177
Range	3000 nmi	2950 nmi	2700 nmi
Takeoff Gross Weight	169,000 lb	139,100 lb	187,700 lb

*Based on Boeing B737-900 aircraft performance [4]

To ensure that the notional aircraft system maintains its market competitiveness, a new redesign is considered for its derivative. Although it is possible to scale down its current subsystems to improve on its gross weight while extending its flight range, the increased competition suggests that its derivative design has to be furnished with new features that can offer an extra edge against competing aircraft. For this example case study, it is taken that the designers have decided to pursue more competitive cabin features.

Parallel with recent focus of technological advancement in aircraft design field, takeoff gross weight can be reduced by converting conventional subsystems into electrical-based. In view of that, this study involves a redesign of current electrical-mechanical-hydraulic flight control subsystem into full EMA implementation. Based on results from a study by NASA and Lockheed Corporation on a 500-passenger transport aircraft, all-electric flight control system is projected to save as much as 28% of its weight in comparison to that of conventional hydraulic-based system [94]. The main breakdown of overall aircraft weight savings projected from this study is illustrated in Figure 101. It should be noted that this study was made during the early 1980’s. Since then, more competitive MEA technologies have been researched and made available that can increase the advantages of all-electric aircraft system.

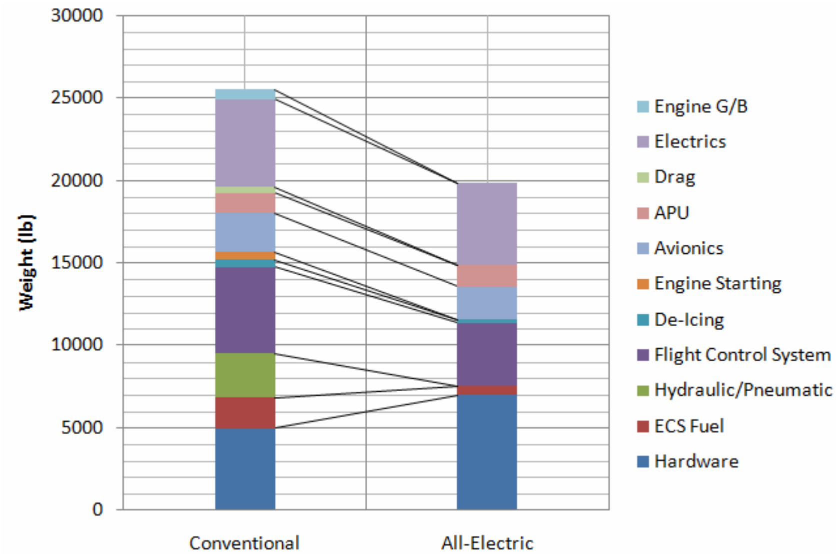


Figure 101: Weight Savings for All-Electric 500-Pax Transport Aircraft [94]

At this point, weight reduction for the notional aircraft system can be achieved with EMA technologies. For this case study, EMA is implemented on its primary flight controls for aileron, elevator and rudder control surfaces, and its flight range is extended to match that of Bombardier C130-ER. In addition, its derivative is to be furnished with context-aware IFE, which is a step forward ahead of current market competition. All initiating change components for the notional aircraft regarding these proposed redesign changes are listed in Table 87. Note that the adaptability and extensibility risks assessments are made based on present MEA description in section 5.1 and the measures for EMA implementation are under similar reasoning to that assigned in first case study for Boeing B727 aircraft.

Subsequently, baseline assessment process is executed and its result is depicted in Figure 102. Primary interest here is relative comparison between adaptability and extensibility risk scores. It can be observed in Figure 102 that redesign process risk score dramatically drops from adaptability approach to that of extensibility, indicating that the redesign risks can be possibly reduced through change propagation. This is a highly favorable condition that greatly supports the redesign decision of the notional aircraft.

Table 87: Initiating Change Components for Notional Aircraft System Model

Proposed Redesign Changes	Initiating Change Component	Change Remarks	Adaptability Assessment		Extensibility Assessment	
			Impact	Cost	Impact	Cost
EMA Primary Flight Controls	Aileron Actuators	Changed to EMA	10	10	4	6
	Elevator Actuators	Changed to EMA	10	10	4	6
	Rudder Actuators	Changed to EMA	10	10	4	6
	Aileron Power Control Unit	Changed to electrical	10	10	1	4
	Elevator Power Control Unit	Changed to electrical	10	10	1	4
	Rudder Power Control Unit	Changed to electrical	10	10	1	4
Context-Aware Cabin IFE	Flight Entertainment Control Unit	Substitute with several new units*	6	10	6	10

* Refer to previous Figure 86

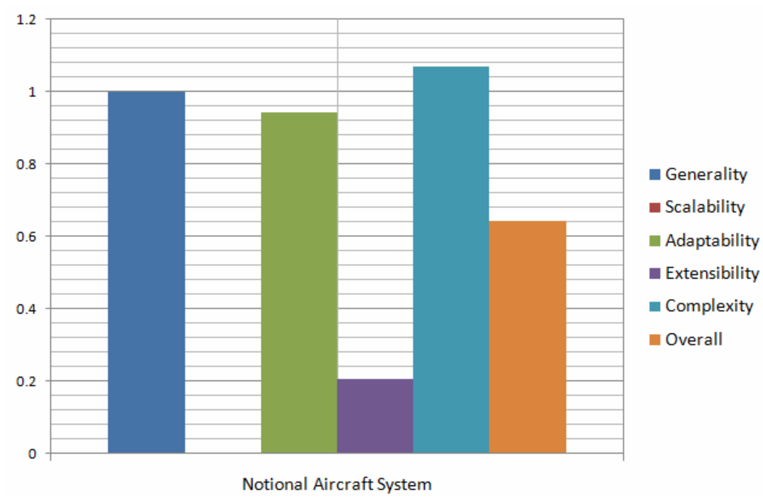


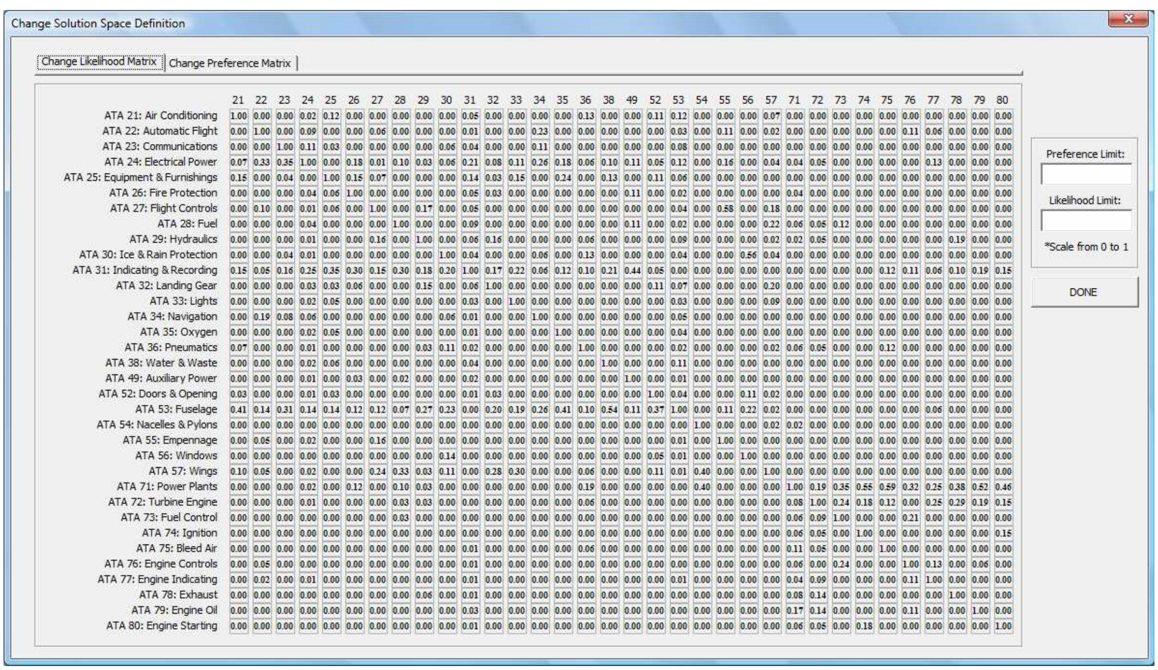
Figure 102: Baseline Assessment for Notional Aircraft System Model

Another thing to note from this result is the slightly increased complexity of its derivative design in relative to its current system composition. This is mainly due to addition of new parts to install context-aware IFE capabilities onboard the aircraft system. On the whole, it is concluded based on this result that the proposed changes are worth pursuing.

5.3.3 Step 3: Change Plan Generation

Once risks associated with the redesign proposal have been concluded to be manageable and competitive enough against pursuing original aircraft development, the next step is to generate possible ways to implement the proposed changes into the baseline design. This basically explores how the current baseline system design architecture can accommodate suggested modification to accomplish the target requirements. The first procedure for this third step of SPEC method is to define change solution space for the redesign problem at hand. In order to establish this, change likelihood and change preference matrices for the notional aircraft system have to be constructed.

As indicated in previous Chapter 4, change likelihood matrix is directly derived based on design characteristics of the notional aircraft. Instead of using historical change data, the likelihood of having to change one subsystem as a result of modification made on another is aptly reflected by the level of interconnectivities that exist between them. For this case study, this matrix is automatically generated from its model and is shown in Figure 103.



	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	38	49	52	53	54	55	56	57	71	72	73	74	75	76	77	78	79	80
ATA 21: Air Conditioning	1.00	0.00	0.00	0.02	0.12	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.11	0.12	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 22: Automatic Flight	0.00	1.00	0.00	0.09	0.00	0.00	0.06	0.00	0.00	0.00	0.01	0.00	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.11	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.11	0.06	0.00	0.00	0.00
ATA 23: Communications	0.00	0.00	1.00	0.11	0.03	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 24: Electrical Power	0.07	0.33	0.35	1.00	0.00	0.18	0.01	0.10	0.03	0.06	0.21	0.08	0.11	0.26	0.18	0.06	0.10	0.11	0.05	0.12	0.00	0.16	0.00	0.04	0.04	0.05	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00
ATA 25: Equipment & Furnishings	0.15	0.00	0.04	0.00	1.00	0.15	0.07	0.00	0.00	0.00	0.14	0.03	0.15	0.00	0.24	0.00	0.13	0.00	0.11	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 26: Fire Protection	0.00	0.00	0.00	0.04	0.06	1.00	0.00	0.00	0.00	0.00	0.05	0.03	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.02	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 27: Flight Controls	0.00	0.10	0.00	0.01	0.06	0.00	1.00	0.00	0.17	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.58	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 28: Fuel	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.02	0.00	0.00	0.00	0.22	0.06	0.05	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 29: Hydraulics	0.00	0.00	0.00	0.01	0.00	0.00	0.16	0.00	1.00	0.00	0.06	0.16	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.02	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00
ATA 30: Ice & Rain Protection	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	1.00	0.04	0.00	0.00	0.06	0.00	0.13	0.00	0.00	0.00	0.04	0.00	0.00	0.56	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 31: Indicating & Recording	0.15	0.05	0.16	0.25	0.35	0.30	0.15	0.30	0.18	0.20	1.00	0.17	0.22	0.06	0.12	0.10	0.21	0.44	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.11	0.06	0.10	0.19	0.15
ATA 32: Landing Gear	0.00	0.00	0.00	0.03	0.03	0.06	0.00	0.00	0.15	0.00	0.06	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.07	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 33: Lights	0.00	0.00	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.03	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 34: Navigation	0.00	0.19	0.08	0.06	0.00	0.00	0.00	0.00	0.00	0.06	0.01	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 35: Oxygen	0.00	0.00	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 36: Pneumatics	0.07	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03	0.11	0.02	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.06	0.05	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00
ATA 38: Water & Waste	0.00	0.00	0.00	0.02	0.06	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 49: Auxiliary Power	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 52: Doors & Opening	0.03	0.00	0.00	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.04	0.00	0.00	0.11	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 53: Fuselage	0.41	0.14	0.31	0.14	0.14	0.12	0.12	0.07	0.27	0.23	0.00	0.20	0.19	0.26	0.41	0.10	0.54	0.11	0.37	1.00	0.00	0.11	0.22	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00
ATA 54: Nacelles & Pylons	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 55: Empennage	0.00	0.05	0.00	0.02	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 56: Windows	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.01	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 57: Wings	0.10	0.05	0.00	0.02	0.00	0.00	0.24	0.33	0.03	0.11	0.00	0.28	0.30	0.00	0.00	0.06	0.00	0.00	0.11	0.01	0.40	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ATA 71: Power Plants	0.00	0.00	0.00	0.02	0.00	0.12	0.00	0.10	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	1.00	0.19	0.35	0.55	0.59	0.32	0.25	0.38	0.52	0.46
ATA 72: Turbine Engine	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	1.00	0.24	0.18	0.12	0.00	0.25	0.29	0.19	0.15
ATA 73: Fuel Control	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.09	1.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00
ATA 74: Ignition	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.15
ATA 75: Bleed Air	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.05	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
ATA 76: Engine Controls	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.24	0.00	0.00	1.00	0.13	0.00	0.06	0.00
ATA 77: Engine Indicating	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.04	0.09	0.00	0.00	0.00	0.11	1.00	0.00	0.00	0.00
ATA 78: Exhaust	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.14	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
ATA 79: Engine Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.14	0.00	0.00	0.00	0.11	0.00	0.00	1.00	0.00
ATA 80: Engine Starting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.00	0.18	0.00	0.00	0.00	0.00	0.00	1.00

Figure 103: Change Likelihood Matrix for Notional Aircraft System

The change likelihood matrix in Figure 103 can be read as follows. Each value represents estimated probability that subsystem in the corresponding row will need to be changed if subsystem in the column has been modified. For instance, value in fourth column of the first row indicates that, if electrical power subsystem is modified, there is a 2% chance that air conditioning subsystem will be subsequently changed. This estimation is based on the fact that 2% of total interconnections that electrical power subsystem has with other subsystems are linked to air conditioning subsystem.

Resultant subsystem change likelihood ranking is depicted in Figure 104. As expected, the high-ranked subsystems are those heavily interconnected with other subsystems. For instance, fuselage is the highest-ranked subsystem and this indicates that changes made on any aircraft subsystems have a big potential to also impact the fuselage. This condition is primarily based on fuselage’s role to house and protect airframe subsystems, requiring it to provide sufficient onboard volumetric space for them. Power plant subsystem, which also has a similar role to fuselage but for propulsion system, has been ranked second on the list. Based on knowledge of subsystems interconnection within the notional aircraft system design, it is concluded that this likelihood ranking correctly predicts the order of subsystems that are most likely to be modified in any redesign case.

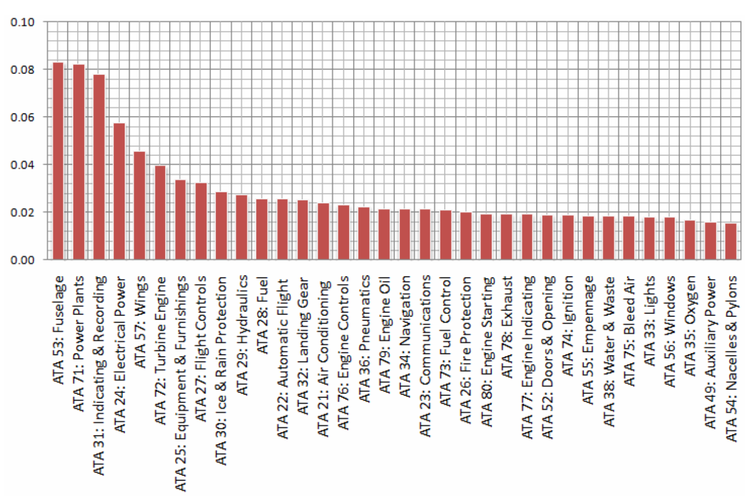


Figure 104: Subsystem Change Likelihood Ranking for Notional Aircraft System

On the other hand, subsystem change preference matrix is to be defined by designers in accordance to their company's inclination or management policy. This matrix is intended to weigh in such considerations into decision-making process for change solution space. In this example case study, change preference ranking is determined based on subsystem costs. It is simply assumed that the higher the subsystem cost is, the less preferable it is to be modified. According to Cronin, costs for conventional aircraft system can be broken down as presented in Figure 105.

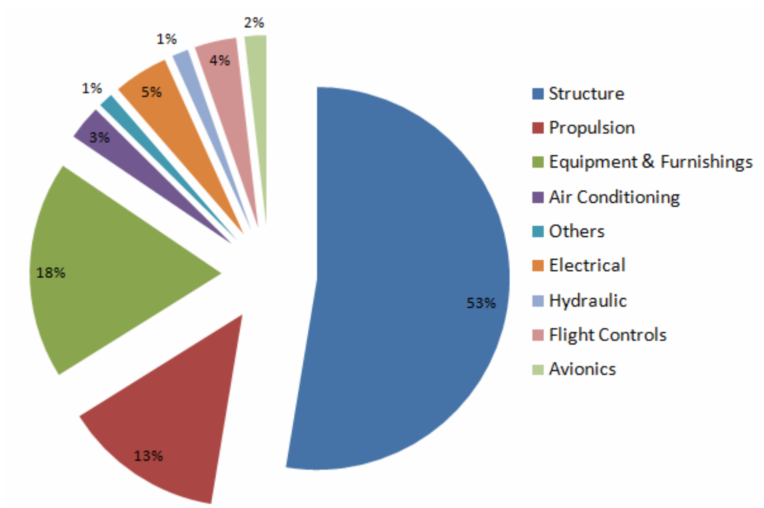


Figure 105: Estimated System Cost Breakdown for Conventional Aircraft [94]

Using information in Figure 105 as the basis for subsystem pairwise comparison, change preference matrix in Figure 106 is derived for the notional aircraft system. The qualitative measurement of change preference between paired subsystems is assigned according to the rating scale defined in Table 67. This change preference matrix is a reciprocal matrix. Based on the assigned value in Figure 106 between air conditioning and automatic flight subsystems, for instance, the latter is the more preferred choice whenever designers have to propagate the change effects to either one of them. This assumption is made based on the higher cost of air conditioning subsystem in relative to automatic flight control, as can be inferred from Figure 105. Overall subsystem change preference ranking is depicted in Figure 107.

	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	38	49	52	53	54	55	56	57	71	72	73	74	75	76	77	78	79	80
ATA 21: Air Conditioning	1.00	0.20	0.20	10.0	10.0	0.10	5.00	0.10	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 22: Automatic Flight	5.00	1.00	1.00	10.0	10.0	0.10	1.00	0.20	5.00	0.20	1.00	5.00	1.00	1.00	0.20	5.00	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 23: Communications	5.00	1.00	1.00	10.0	10.0	0.20	5.00	1.00	5.00	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 24: Electrical Power	0.10	0.10	0.10	1.00	10.0	0.10	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 25: Equipment & Furnishings	0.10	0.10	0.10	0.10	1.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 26: Fire Protection	10.0	10.0	5.00	10.0	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 27: Flight Controls	0.20	1.00	0.20	5.00	10.0	0.10	1.00	0.20	5.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 28: Fuel	10.0	5.00	1.00	10.0	10.0	0.10	5.00	1.00	5.00	0.10	0.10	0.10	0.10	0.10	0.10	1.00	0.10	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 29: Hydraulics	5.00	0.20	0.20	10.0	10.0	0.10	0.20	0.20	1.00	0.10	0.10	0.10	0.10	0.10	0.10	1.00	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 30: Ice & Rain Protection	10.0	5.00	1.00	10.0	10.0	0.10	10.0	10.0	10.0	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 31: Indicating & Recording	10.0	1.00	1.00	10.0	10.0	0.10	10.0	10.0	10.0	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 32: Landing Gear	10.0	0.20	0.10	10.0	10.0	0.10	10.0	10.0	10.0	0.10	0.10	1.00	0.10	0.10	0.10	10.0	0.10	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 33: Lights	10.0	1.00	1.00	10.0	10.0	0.10	10.0	10.0	10.0	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 34: Navigation	10.0	1.00	1.00	10.0	10.0	0.10	10.0	10.0	10.0	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 35: Oxygen	10.0	5.00	1.00	10.0	10.0	0.10	10.0	10.0	10.0	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 36: Pneumatics	10.0	0.20	0.10	10.0	10.0	0.10	10.0	1.00	1.00	0.10	0.10	0.10	0.10	0.10	0.10	1.00	0.10	0.10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 38: Water & Waste	10.0	10.0	1.00	10.0	10.0	0.10	10.0	10.0	10.0	1.00	1.00	10.0	1.00	1.00	1.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 49: Auxiliary Power	10.0	10.0	0.10	10.0	10.0	0.10	10.0	1.00	10.0	0.10	0.10	1.00	0.10	0.10	0.10	10.0	0.10	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 52: Doors & Opening	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.00	10.0	10.0	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 53: Fuselage	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ATA 54: Nacelles & Pylons	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	1.00	5.00	0.20	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 55: Empennage	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.20	1.00	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 56: Windows	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.00	10.0	5.00	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 57: Wings	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	0.10	0.10	1.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ATA 71: Power Plants	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	1.00	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
ATA 72: Turbine Engine	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	1.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ATA 73: Fuel Control	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 74: Ignition	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 75: Bleed Air	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 76: Engine Controls	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 77: Engine Indicating	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 78: Exhaust	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 79: Engine Oil	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ATA 80: Engine Starting	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	10.0	0.10	1.00	0.10	10.0	0.10	10.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

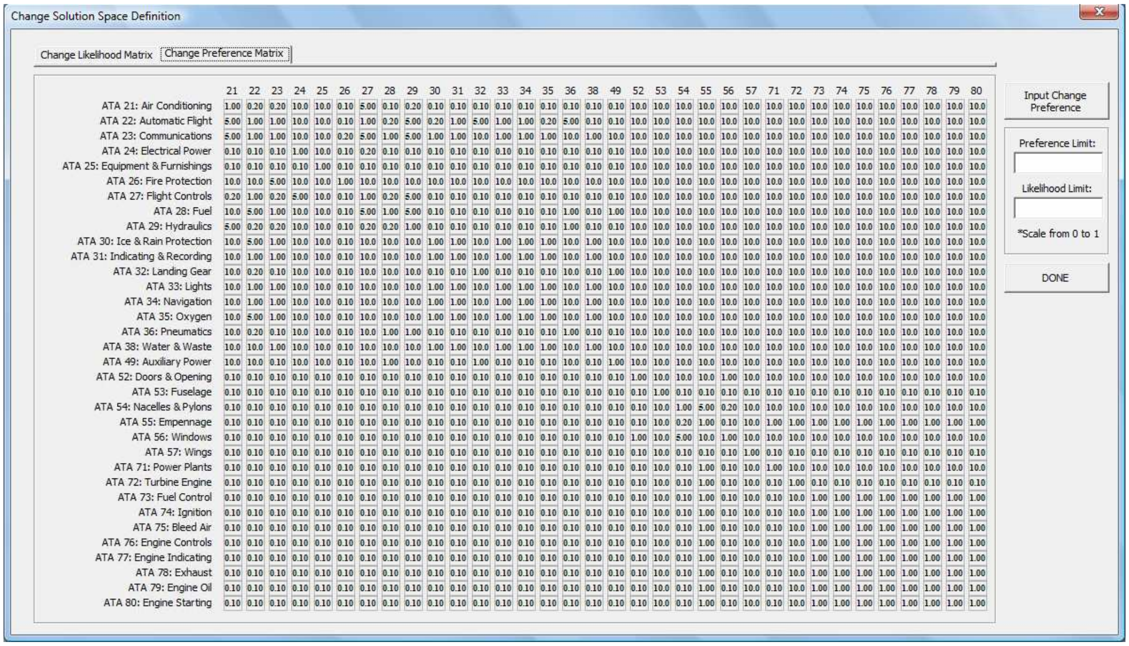


Figure 106: Change Preference Matrix for Notional Aircraft System

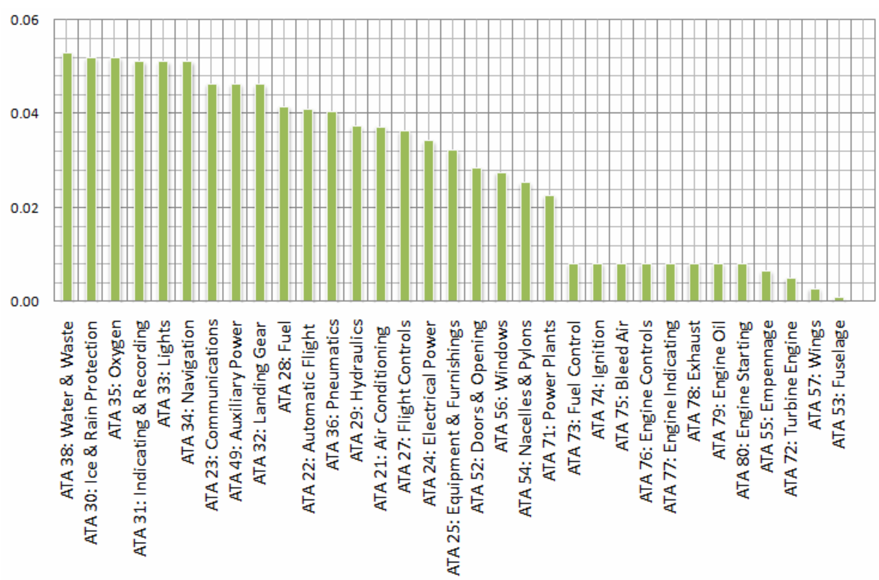


Figure 107: Subsystem Change Preference Ranking for Notional Aircraft System

In Figure 107, major structural and propulsion subsystems have been ranked at bottom of this change preference list. This is in line with provided cost information in Figure 105, which implies that they are the costliest among other aircraft subsystems and therefore are less preferred to be modified. While fuselage topped the change likelihood list, it is however the lowest ranked subsystem in terms of change preference. This means that it is associated with a high level of redesign risks since although it is not preferred to change, modifications made in other subsystems tend to propagate their change effects to it. By allowing fuselage to be subsequently changed, it will affect many other subsystems and can create an "avalanche" of change propagation. To cope with this situation, fuselage's change role can be designated as a "constant" and by doing so; proposed changes have to be implemented around existing fuselage structure. To better observe this kind of change likelihood and change preference situation, their ranking scores can be mapped together on a single plot as shown in Figure 108.

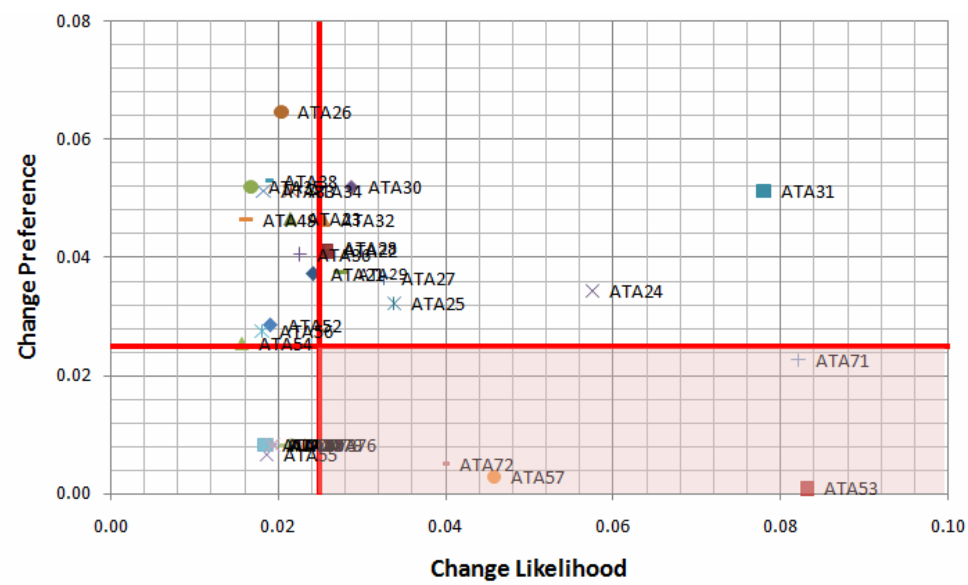


Figure 108: Change Likelihood and Preference for Notional Aircraft Subsystems

Constraint limit for both scores, which if violated indicates that the subsystem currently has a higher redesign risk than favored, can be set by designers. If all 34 different aircraft subsystems have a similar level of change likelihood and change preference, their score is equal to 1/34 = 0.029. This value is set as the constraint limit for this example case study as indicated in Figure 108. The shaded red area in the figure highlights subsystems that are inside the high-risk region. As expected, fuselage is among these subsystems that also include power plant, wing and turbine engine. These four subsystems are assigned with a "constant" change role as illustrated in Figure 109.

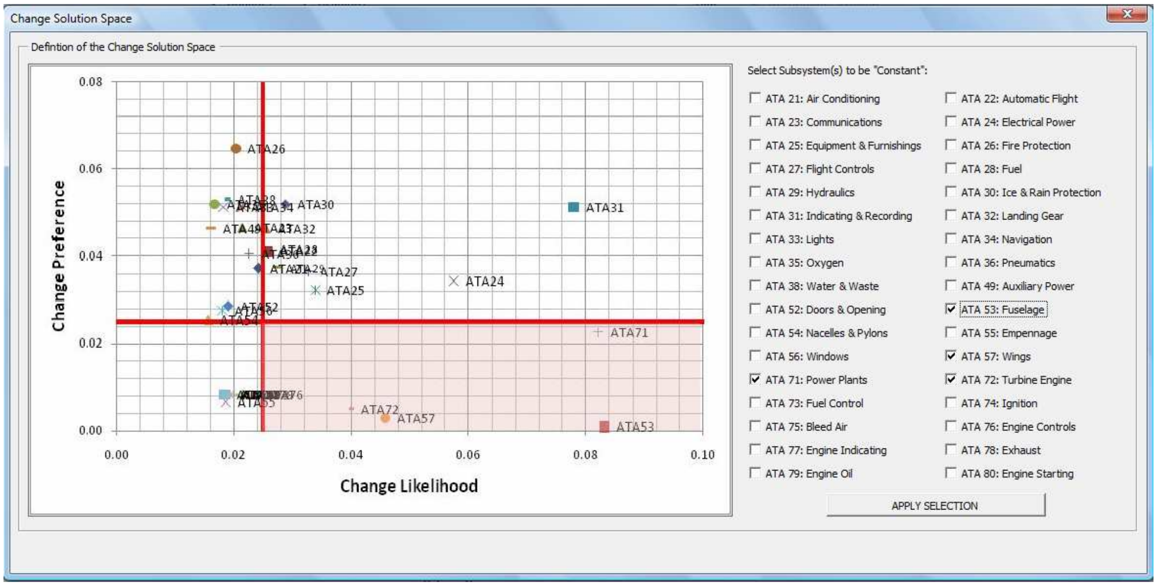


Figure 109: "Constant" Change Role Assignment in SPEC Support Tool

With selection of "constant" subsystems, change solution space for generating alternative change implementation plans is now set. The implementation of proposed modification is not allowed to affect "constant" subsystems, which effectively limits propagation paths of change effects. The change plan generation interface is shown in Figure 110.

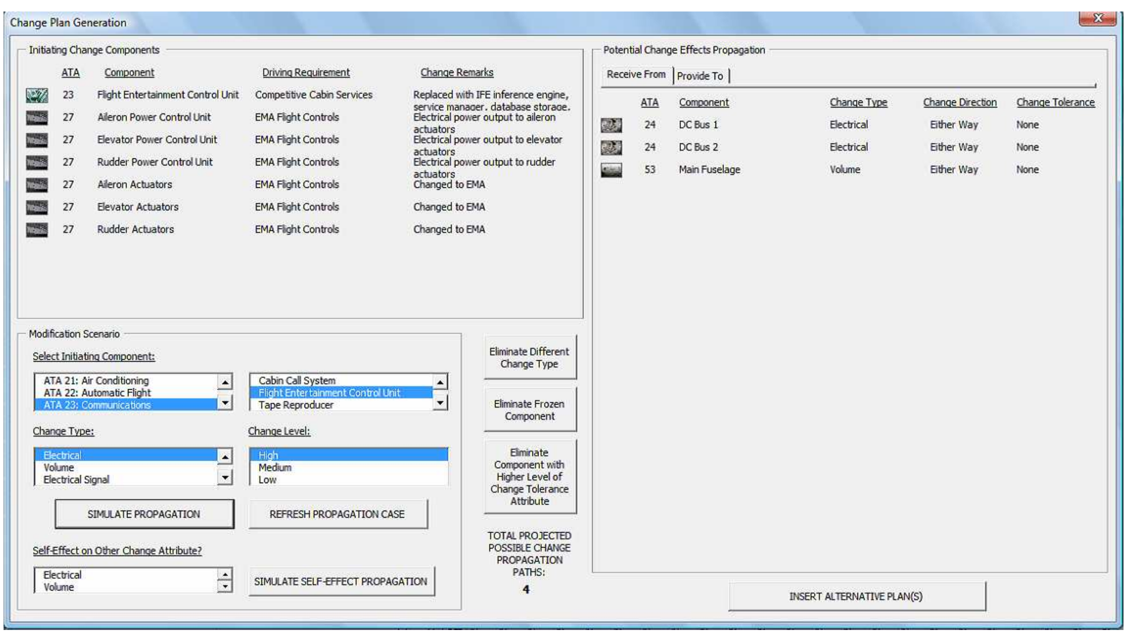


Figure 110: Change Plan Generation Environment in SPEC Support Tool

To demonstrate change effects propagation, three-step propagation that results from the implementation of new in-flight entertainment control units for context-aware IFE system is illustrated in Figure 111. The red boxes indicate that the particular branch of predicted change propagation paths is terminated by the corresponding component. For instance, since fuselage is designated as a "constant", no change effect is allowed to be passed to it and thus the propagating component has to absorb the change impacts into its own design instead. To simplify this example case study, none of other electrical-based components that are connected to the electrical power buses is being considered for reduction in their power inputs to accommodate the increased demand of flight entertainment system.

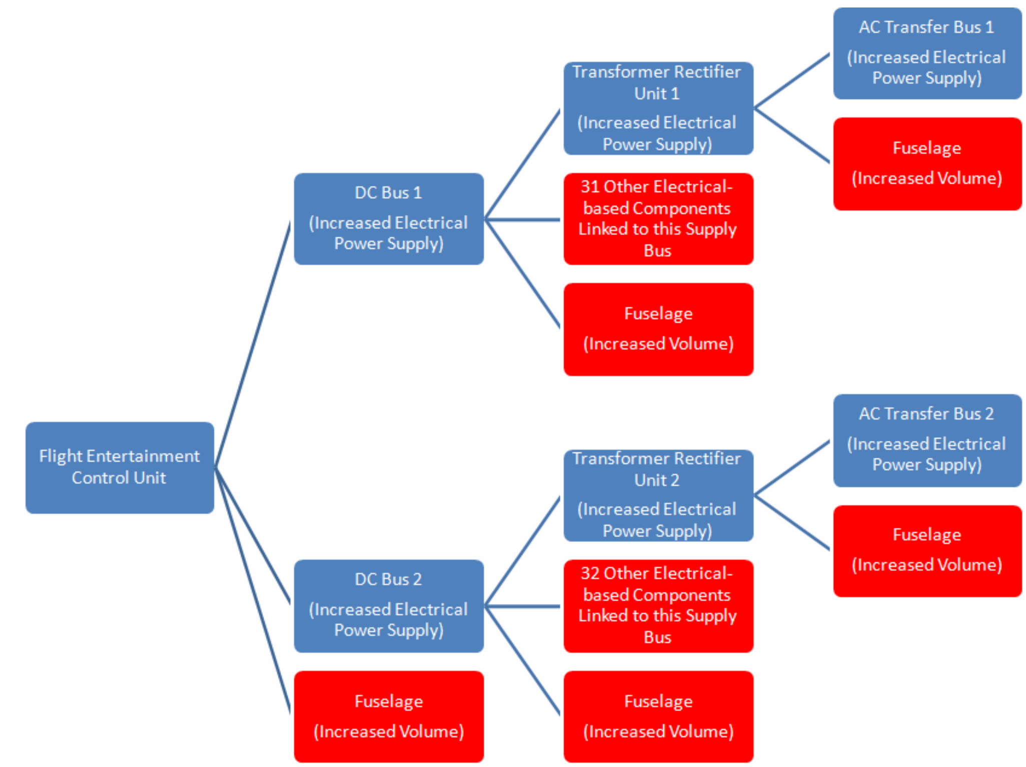


Figure 111: Change Effects Propagation from IFE Control Modification

The predicted propagation paths from implementation of context-aware IFE system and EMA flight controls are summarized in Figure 112. This propagation matrix is read from row to column, indicating that potential change effects are transmitted from modifications made on row components to the design of column components. Components of electrical power distribution and generation are affected by both initiating system design changes. If their implementation is individually planned as suggested by several change methods, their cumulative effects on these components might not be realized until later stages. This overlooked condition can induce redesign iterations that prolong the development process and increase its costs.

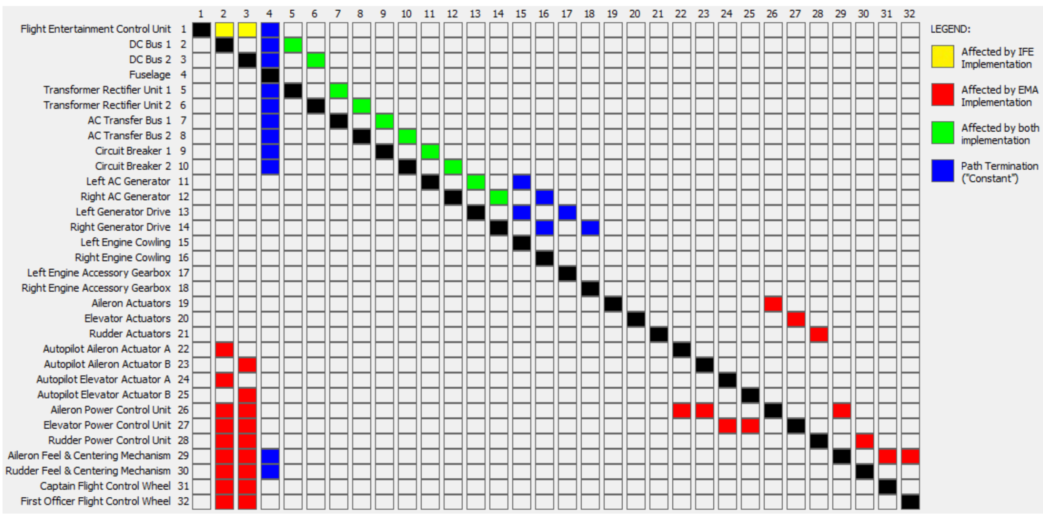


Figure 112: Summary of Predicted Potential Change Effects Propagation Paths

By varying the change roles for affected components in Figure 112, several change plans can be generated. Four different change plans have been effectively constructed for this example case study and they are described in Table 88. Notice different change roles that are assigned for the components, which are a key element that distinguish the alternative plans. This role assignment dictates the control of change effects propagation and hence the amount of affected components within each plan. For instance, by changing the role of aileron power unit from "absorber" to "carrier" with regards to electrical signal inputs for aileron control (from Plan 1 to Plan 2), it propagates the change effects to aileron feel and centering mechanism, and flight control wheels. Accordingly, aileron power control unit no longer needs to be equipped with mechanical-to-electrical transducer capability. Instead, supply of roll control inputs from the cockpit flight control wheels should readily be converted into an electrical-based mechanism.

Table 88: Change Alternative Plans for Notional Aircraft

Plan	Modified Component	Affected Change Attribute	Change Role	Change Level
1	IFE Control Unit	Volume	Absorber	-
		Electrical	Absorber	-
	Aileron Actuators Elevator Actuators Rudder Actuators	Volume	Absorber	-
		Electrical	Carrier	Medium
	Aileron Power Control Unit Elevator Power Control Unit Rudder Power Control Unit	Volume	Absorber	-
		Electrical	Carrier	Medium
		Electrical Signal	Absorber	-
	Autopilot Aileron Actuators A Autopilot Aileron Actuators B Autopilot Elevator Actuators A Autopilot Elevator Actuators B	Volume	Absorber	-
		Electrical	Absorber	-
	DC Bus 1 DC Bus 2 TRU 1 TRU 2 AC Bus 1 AC Bus 2 Circuit Breaker 1 Circuit Breaker 2	Volume	Absorber	-
		Electrical	Carrier	Medium
	Left AC Generator Right AC Generator	Volume	Absorber	-
		Mechanical/Force	Absorber	Medium
2	IFE Control Unit	Volume	Absorber	-
		Electrical	Carrier	Low
	Aileron Actuators Elevator Actuators Rudder Actuators	Volume	Absorber	-
		Electrical	Carrier	Medium
	Aileron Power Control Unit Elevator Power Control Unit Rudder Power Control Unit	Volume	Absorber	-
		Electrical	Carrier	Medium
		Electrical Signal	Carrier	Low
	Aileron Feel & Centering Rudder Feel & Centering Captain Flight Control Wheel F/O Flight Control Wheel	Electrical Signal	Absorber	-
	Autopilot Aileron Actuators A Autopilot Aileron Actuators B Autopilot Elevator Actuators A Autopilot Elevator Actuators B	Volume	Absorber	-
		Electrical	Carrier	Medium
	DC Bus 1 DC Bus 2 TRU 1 TRU 2 AC Bus 1 AC Bus 2 Circuit Breaker 1 Circuit Breaker 2	Volume	Absorber	-
		Electrical	Carrier	High
	Left AC Generator Right AC Generator	Volume	Absorber	-
		Mechanical/Force	Absorber	High

Table 88: Change Alternative Plans for Notional Aircraft (cont.)

Plan	Modified Component	Affected Change Attribute	Change Role	Change Level
3	IFE Control Unit	Volume	Absorber	-
		Electrical	Carrier	Low
	Aileron Actuators Elevator Actuators Rudder Actuators	Volume	Absorber	-
		Electrical	Carrier	Medium
	Aileron Power Control Unit Elevator Power Control Unit Rudder Power Control Unit	Volume	Absorber	-
		Electrical	Carrier	Medium
		Electrical Signal	Absorber	-
	Autopilot Aileron Actuators A Autopilot Aileron Actuators B Autopilot Elevator Actuators A Autopilot Elevator Actuators B	Volume	Absorber	-
		Electrical	Absorber	-
	DC Bus 1 DC Bus 2 TRU 1 TRU 2 AC Bus 1 AC Bus 2 Circuit Breaker 1 Circuit Breaker 2	Volume	Absorber	-
		Electrical	Carrier	Medium
	Left AC Generator Right AC Generator Left Generator Drive Right Generator Drive	Volume	Absorber	-
		Mechanical/Force	Absorber	Medium
4	IFE Control Unit	Volume	Absorber	-
		Electrical	Absorber	-
	Aileron Actuators Elevator Actuators Rudder Actuators	Volume	Absorber	-
		Electrical	Carrier	Medium
	Aileron Power Control Unit Elevator Power Control Unit Rudder Power Control Unit	Volume	Absorber	-
		Electrical	Carrier	Medium
		Electrical Signal	Carrier	Low
	Aileron Feel & Centering Rudder Feel & Centering Captain Flight Control Wheel F/O Flight Control Wheel	Electrical Signal	Absorber	-
	Autopilot Aileron Actuators A Autopilot Aileron Actuators B Autopilot Elevator Actuators A Autopilot Elevator Actuators B	Volume	Absorber	-
		Electrical	Carrier	Medium
	DC Bus 1 DC Bus 2 TRU 1 TRU 2 AC Bus 1 AC Bus 2 Circuit Breaker 1 Circuit Breaker 2	Volume	Absorber	-
		Electrical	Carrier	High
	Left AC Generator Right AC Generator	Volume	Absorber	-
		Mechanical/Force	Absorber	-

5.3.4 Step 4: Change Impact Assessment

For each generated change implementation plan outlined in Table 88, their process risks and impacts on performance of the notional aircraft have to be investigated. Firstly, the assessment of process risks for each alternative plan is made based on the explanation of MEA technologies in section 5.1, as summarized in Table 89. Its change process impact rating is tailored to current SRL level of related technologies and assigned based on the change impact and cost rating scales in Table 60 and Table 61, respectively.

As can be observed in Table 89, process risk for the alternative change plans is different to each other. By controlling change effects propagation with assignment of component's change role, redesign process risk can be effectively managed. In addition, by comparing Plan 1 and Plan 2, the number of affected components in former change implementation plan is slightly less than the latter. But even though Plan 2 affects four more components than Plan 1, its overall score for process risk is notably less than Plan 1. This observation shows that minimum number of affected components, which is the common measure of redesign effectiveness in many available methods; do not guarantee the lowest process risks or the easiest change implementation process. The normalized process risks for the change implementation alternative plans to the maximum score among them are shown in Figure 113 and if solely based on the process risk, Plan 2 appears to be the best possible way to implement both context-aware IFE system and EMA primary flight controls into the notional aircraft system.

Table 89: Process Risks Assessment for Change Alternative Plans

Plan	Modified Component	Impact Rating	Cost Rating	Reference Technology	Total Risk
1	IFE Control Unit	8	10	Context-Aware IFE	80
	Aileron Actuators	4	6	EMA Implementation	24
	Elevator Actuators	4	6		24
	Rudder Actuators	4	6		24
	Aileron Power Control Unit	6	10		60
	Elevator Power Control Unit	6	10		60
	Rudder Power Control Unit	6	10		60
	Autopilot Aileron Actuators A	6	6		36
	Autopilot Aileron Actuators B	6	6		36
	Autopilot Elevator Actuators A	6	6		36
	Autopilot Elevator Actuators B	6	6		36
	DC Bus 1	1	4	Power Electronics for Advanced Electrical Networking	4
	DC Bus 2	1	4		4
	TRU 1	4	4		16
	TRU 2	4	4		16
	AC Bus 1	1	4		4
	AC Bus 2	1	4		4
	Circuit Breaker 1	4	4		16
	Circuit Breaker 2	4	4		16
	Left AC Generator	4	10	VSFC High Power Starter-Generator	40
	Right AC Generator	4	10		40
				TOTAL	636
2	IFE Control Unit	4	10	Context-Aware IFE	40
	Aileron Actuators	4	6	EMA Implementation	24
	Elevator Actuators	4	6		24
	Rudder Actuators	4	6		24
	Aileron Power Control Unit	4	6		24
	Elevator Power Control Unit	4	6		24
	Rudder Power Control Unit	4	6		24
	Aileron Feel & Centering	1	1	Flight-by-Wire Flight Controls	1
	Rudder Feel & Centering	1	1		1
	Captain Flight Control Wheel	1	1		1
	F/O Flight Control Wheel	1	1		1
	Autopilot Aileron Actuators A	4	6	EMA Implementation	24
	Autopilot Aileron Actuators B	4	6		24
	Autopilot Elevator Actuators A	4	6		24
	Autopilot Elevator Actuators B	4	6		24
	DC Bus 1	4	4	Power Electronics for Advanced Electrical Networking	16
	DC Bus 2	4	4		16
	TRU 1	4	4		16
	TRU 2	4	4		16
	AC Bus 1	4	4		16
	AC Bus 2	4	4		16
	Circuit Breaker 1	4	4		16
	Circuit Breaker 2	4	4		16
	Left AC Generator	6	10	VSFC High Power Starter-Generator	60
	Right AC Generator	6	10		60
				TOTAL	532

Table 89: Process Risks Assessment for Change Alternative Plans (cont.)

Plan	Modified Component	Impact Rating	Cost Rating	Reference Technology	Total Risk
3	IFE Control Unit	4	10	Context-Aware IFE	40
3	Aileron Actuators	4	6	EMA Implementation	24
3	Elevator Actuators	4	6	EMA Implementation	24
3	Rudder Actuators	4	6	EMA Implementation	24
3	Aileron Power Control Unit	6	10	EMA Implementation	60
3	Elevator Power Control Unit	6	10	EMA Implementation	60
3	Rudder Power Control Unit	6	10	EMA Implementation	60
3	Autopilot Aileron Actuators A	6	6	EMA Implementation	36
3	Autopilot Aileron Actuators B	6	6	EMA Implementation	36
3	Autopilot Elevator Actuators A	6	6	EMA Implementation	36
3	Autopilot Elevator Actuators B	6	6	EMA Implementation	36
3	DC Bus 1	1	4	Power Electronics for Advanced Electrical Networking	4
3	DC Bus 2	1	4	Power Electronics for Advanced Electrical Networking	4
3	TRU 1	4	4	Power Electronics for Advanced Electrical Networking	16
3	TRU 2	4	4	Power Electronics for Advanced Electrical Networking	16
3	AC Bus 1	1	4	Power Electronics for Advanced Electrical Networking	4
3	AC Bus 2	1	4	Power Electronics for Advanced Electrical Networking	4
3	Circuit Breaker 1	4	4	Power Electronics for Advanced Electrical Networking	16
3	Circuit Breaker 2	4	4	Power Electronics for Advanced Electrical Networking	16
3	Left AC Generator	4	10	VSFC High Power Starter-Generator	40
3	Right AC Generator	4	10	VSFC High Power Starter-Generator	40
				TOTAL	596
4	IFE Control Unit	8	10	Context-Aware IFE	80
4	Aileron Actuators	4	6	EMA Implementation	24
4	Elevator Actuators	4	6	EMA Implementation	24
4	Rudder Actuators	4	6	EMA Implementation	24
4	Aileron Power Control Unit	4	6	EMA Implementation	24
4	Elevator Power Control Unit	4	6	EMA Implementation	24
4	Rudder Power Control Unit	4	6	EMA Implementation	24
4	Aileron Feel & Centering	1	1	Flight-by-Wire Flight Controls	1
4	Rudder Feel & Centering	1	1	Flight-by-Wire Flight Controls	1
4	Captain Flight Control Wheel	1	1	Flight-by-Wire Flight Controls	1
4	F/O Flight Control Wheel	1	1	Flight-by-Wire Flight Controls	1
4	Autopilot Aileron Actuators A	4	6	EMA Implementation	24
4	Autopilot Aileron Actuators B	4	6	EMA Implementation	24
4	Autopilot Elevator Actuators A	4	6	EMA Implementation	24
4	Autopilot Elevator Actuators B	4	6	EMA Implementation	24
4	DC Bus 1	4	4	Power Electronics for Advanced Electrical Networking	16
4	DC Bus 2	4	4	Power Electronics for Advanced Electrical Networking	16
4	TRU 1	4	4	Power Electronics for Advanced Electrical Networking	16
4	TRU 2	4	4	Power Electronics for Advanced Electrical Networking	16
4	AC Bus 1	4	4	Power Electronics for Advanced Electrical Networking	16
4	AC Bus 2	4	4	Power Electronics for Advanced Electrical Networking	16
4	Circuit Breaker 1	4	4	Power Electronics for Advanced Electrical Networking	16
4	Circuit Breaker 2	4	4	Power Electronics for Advanced Electrical Networking	16
4	Left AC Generator	6	10	VSFC High Power Starter-Generator	60
4	Right AC Generator	6	10	VSFC High Power Starter-Generator	60
				TOTAL	572

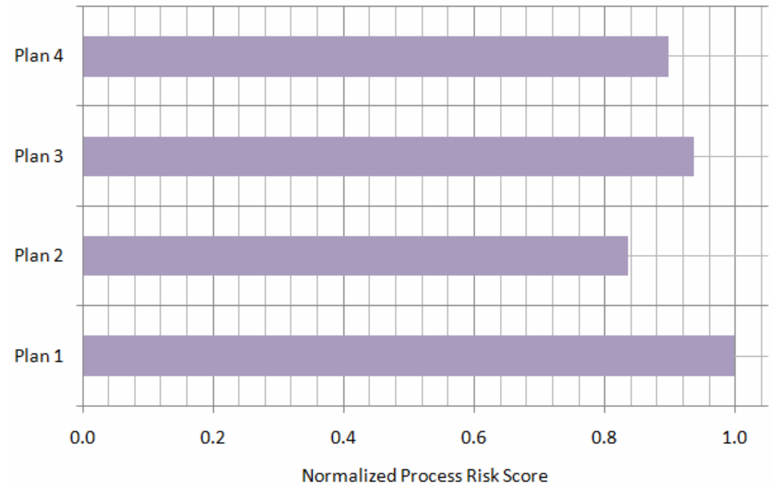


Figure 113: Comparison of Process Risk Scores for Change Alternative Plans

Nonetheless, it is important to study the extent of effects that these design modifications have on the derivative aircraft performance. To assess this aspect of change impacts, the underlying relationships between affected subsystem parameters and interested high-level aircraft system metrics are required. In application of proposed SPEC methodology, it is assumed that these relationships are known and available to designers, and the procedure for this methodology does not cover their establishment. For this case study, an estimated relationship is constructed using Flight Optimization System (FLOPS) software package and details for its build-up are presented in Appendix C. Only one system level metric is considered here, which is gross weight.

Another system level metric that is of high interest in this redesign case is flight range. Although change plans derived in previous step do not include any scaling up or down of subsystems to extend the derivative aircraft range, this is automatically done in FLOPS. While creating input file for FLOPS, the desired flight range is set to 2950 nmi and all design characteristics for "constant" subsystems are frozen by using override parameters. It is assumed that the automated design scaling of subsystems is made without changing their architectural composition or affecting "constant" subsystems. Gross weight effects from this automated design scaling are taken to be the same for each change alternative plan and thus could be safely omitted from the change plans for simplicity.

The constructed subsystem-system weight relationship is presented as follows:

$$\begin{aligned}&Gross\,Weight\ (lb) = 146487 + 25317WFURN + 3190.3WELEC + 2708.1\,FRSC\\&+ 2679.3WAC + 2370.5FRNA + 2353.1WAVONC + 1775.9WHYD + 1696.7WAPU\\&+ 1187.2WFSYS + 817.8WPMSC + 792.7WIN + 203.6WOIL\end{aligned}$$

Equation 21

$$\begin{aligned}where:\ &WFURN = Furnishings\ group\ weight,\ \ WELEC = Electrical\ group\ weight\\&FRSC = Surface\ controls\ weight,\ \ WAC = Air\ conditioning\ group\ weight\\&FRNA = Total\ weight\ of\ nacelles\ and/or\ air\ induction\ system\\&WAVONC = Avionics\ group\ weight,\ \ WHYD = Hydraulics\ group\ weight\\&WAPU = Auxiliary\ power\ unit\ weight,\ \ WFSYS = Weight\ of\ fuel\ system\\&WPMSC = Weight\ of\ miscellaneous\ propulsion\ systems\\&WIN = Instrument\ group\ weight,\ \ WOIL = Engine\ oil\ weight\end{aligned}$$

Using this subsystem-system relationship, impending effects of each alternative change plan on the overall aircraft system weight can be estimated. The projected weight effects from affected components are based on provided information in reference literatures and they are tabulated in Table 90.

Accordingly, gross weight for the derivative aircraft that results from each change plan is shown in Table 91. The variation of change roles for components of flight control system seems to have a more significant impact on gross weight based on the estimated effects. When conventional mechanical-based flight controls input mechanism is substituted with electrical wirings, the weight savings simply outweigh the smaller weight increment on electrical power subsystem. On contrary, a computing unit that operates with different level of electrical power inputs does not necessarily vary much in terms of weights based on current state of electronics technology. This is apparent by comparing the estimated gross weight for Plan 1 and Plan 3 with that of Plan 2 and Plan 4 in Table 91.

Table 90: Weight Impact Assessment for Change Alternative Plans

Plan	Modified Component	Estimated Weight Effects	Main Reference
1	IFE Control Unit	+2% of WIN	[207, 208]
	Aileron Actuators	-5% of FRSC -70% of WHYD	[37, 49, 93, 94, 99, 269, 322]
	Elevator Actuators		
	Rudder Actuators		
	Aileron Power Control Unit		
	Elevator Power Control Unit		
	Rudder Power Control Unit		
	Autopilot Aileron Actuators A		
	Autopilot Aileron Actuators B		
	Autopilot Elevator Actuators A		
	Autopilot Elevator Actuators B		
	DC Bus 1	-40% WELEC	[17, 49, 123, 124, 260, 269]
	DC Bus 2		
	TRU 1		
	TRU 2		
	AC Bus 1		
	AC Bus 2		
	Circuit Breaker 1		
	Circuit Breaker 2		
	Left AC Generator		
	Right AC Generator		
2	IFE Control Unit	+2% of WIN	[207, 208]
	Aileron Actuators	-33% of FRSC -70% of WHYD	[37, 49, 93, 94, 99, 269, 322]
	Elevator Actuators		
	Rudder Actuators		
	Aileron Power Control Unit		
	Elevator Power Control Unit		
	Rudder Power Control Unit		
	Aileron Feel & Centering		
	Rudder Feel & Centering		
	Captain Flight Control Wheel		
	F/O Flight Control Wheel		
	Autopilot Aileron Actuators A		
	Autopilot Aileron Actuators B		
	Autopilot Elevator Actuators A		
	Autopilot Elevator Actuators B		
	DC Bus 1	-30% WELEC	[17, 49, 123, 124, 260, 269]
	DC Bus 2		
	TRU 1		
	TRU 2		
	AC Bus 1		
	AC Bus 2		
	Circuit Breaker 1		
	Circuit Breaker 2		
	Left AC Generator		
	Right AC Generator		

Table 90: Weight Impact Assessment for Change Alternative Plans (cont.)

Plan	Modified Component	Estimated Weight Effects	Main Reference
3	IFE Control Unit	+2% of WIN	[207, 208]
	Aileron Actuators	-5% of FRSC -70% of WHYD	[37, 49, 93, 94, 99, 269, 322]
	Elevator Actuators		
	Rudder Actuators		
	Aileron Power Control Unit		
	Elevator Power Control Unit		
	Rudder Power Control Unit		
	Autopilot Aileron Actuators A		
	Autopilot Aileron Actuators B		
	Autopilot Elevator Actuators A		
	Autopilot Elevator Actuators B		
	DC Bus 1	-40% WELEC	[17, 49, 123, 124, 260, 269]
	DC Bus 2		
	TRU 1		
	TRU 2		
	AC Bus 1		
	AC Bus 2		
	Circuit Breaker 1		
	Circuit Breaker 2		
	Left AC Generator		
	Right AC Generator		
4	IFE Control Unit	+2% of WIN	[207, 208]
	Aileron Actuators	-33% of FRSC -70% of WHYD	[37, 49, 93, 94, 99, 269, 322]
	Elevator Actuators		
	Rudder Actuators		
	Aileron Power Control Unit		
	Elevator Power Control Unit		
	Rudder Power Control Unit		
	Aileron Feel & Centering		
	Rudder Feel & Centering		
	Captain Flight Control Wheel		
	F/O Flight Control Wheel		
	Autopilot Aileron Actuators A		
	Autopilot Aileron Actuators B		
	Autopilot Elevator Actuators A		
	Autopilot Elevator Actuators B		
	DC Bus 1	-30% WELEC	[17, 49, 123, 124, 260, 269]
	DC Bus 2		
	TRU 1		
	TRU 2		
	AC Bus 1		
	AC Bus 2		
	Circuit Breaker 1		
	Circuit Breaker 2		
	Left AC Generator		
	Right AC Generator		

Table 91: Estimated Gross Weight for Derivative Aircraft System

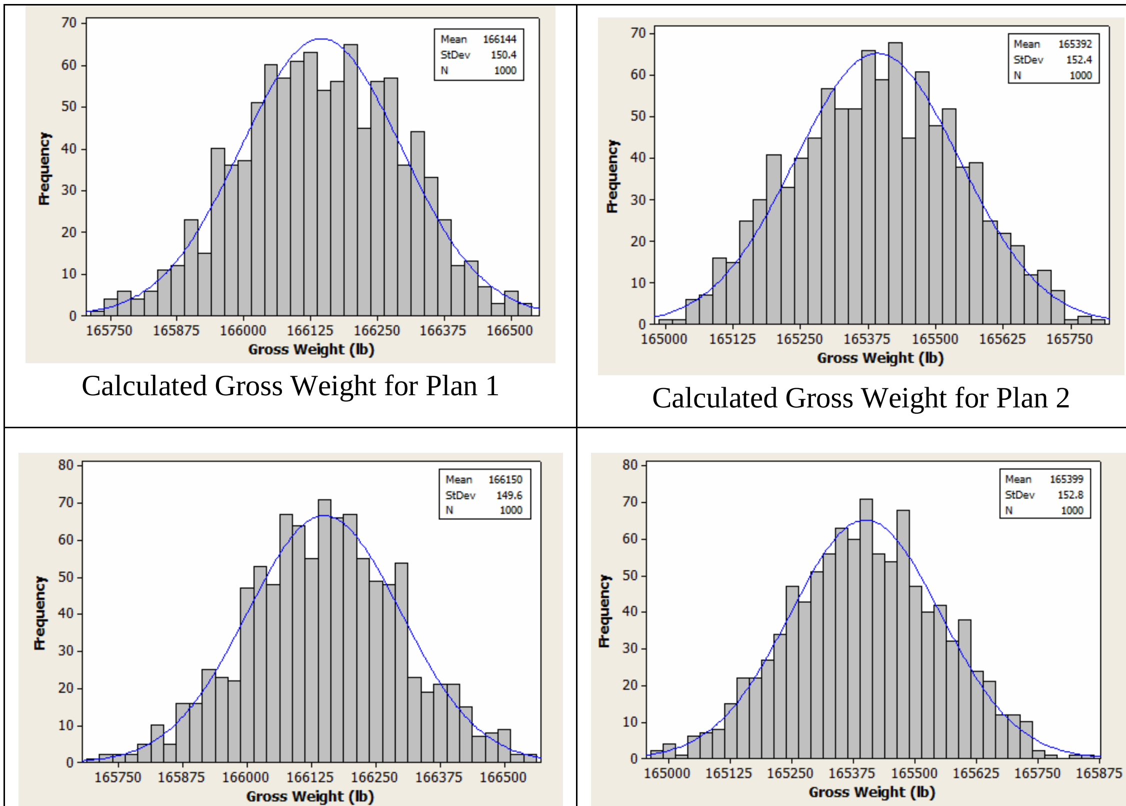
Plan	Gross Weight (lb)
1	166,154.3
2	165,396.1
3	166,154.3
4	165,396.1

Thus far, the change impacts have been deterministically assessed. Nevertheless, none of MEA technologies in this study is fully matured in the context of their proposed system application and hence their impacts are also associated with uncertainties. A probabilistic assessment can be executed instead of the deterministic approach and to demonstrate this, a Monte Carlo Simulation (MCS) for each affected subsystem weight parameter is done. In the lack of absolute knowledge regarding the actual probability distribution for change effects, they are assigned with a triangular distribution. 1000 random cases are executed for each change alternative plan. Instead of a single deterministic value, resultant gross weight from this change impact assessment is now represented as a distribution. In Table 92, the distribution used for elements of the change effects is defined.

Table 92: Triangular Distribution for Subsystem Parameters

Change Plan	Subsystem Parameter	Lower Limit	Mode	Upper Limit
1 & 3	WELEC	0.500	0.600	0.700
	WHYD	0.200	0.300	0.400
	FRSC	0.925	0.950	0.975
	WIN	1.010	1.020	1.030
2 & 4	WELEC	0.500	0.600	0.700
	WHYD	0.200	0.300	0.400
	FRSC	0.640	0.670	0.700
	WIN	1.010	1.020	1.030

Accordingly, calculated distribution for the gross weight of the derivative aircraft in each change alternative plan is shown in Figure 114. Random generation of subsystem weight parameters during the Monte Carlo Simulation process is made using MINITAB software and they are assumed to be additive through previously derived subsystem-system weight relationship from FLOPS. For this probabilistic change impact assessment, the selection process for different change plans can be made at a specified confidence level.



Calculated Gross Weight for Plan 1

Calculated Gross Weight for Plan 2

Calculated Gross Weight for Plan 3

Calculated Gross Weight for Plan 4

Figure 114: Gross Weight Distribution in Probabilistic Change Impact Assessment

5.3.5 Step 5: Change Plan Selection

Back in Step 2, it is assumed that the pursuit of this derivative redesign approach for the notional aircraft system is intended to improve its market competitiveness. This has been proposed to be accomplished by reducing its gross weight while extending its flight range through installation of EMA flight controls, and offering a competitive cabin service with installation of context-aware IFE. To finalize the selection of change alternative plans, subsequent effects from their proposed changes should be weighed if they are justifiable to be further pursued. With target range of the derivative aircraft is set to match the new

Bombardier C130-ER aircraft, comparable gross weight to Airbus A320 (shown in Table 86) is taken as another target requirement considering passenger capacity of the notional aircraft. The deterministic performance and process risk indexes for each change plan are listed in Table 93 and the performance-risk plot is constructed in Figure 115. In addition, to observe if the conclusion from probabilistic change impact assessment will vary from that of the deterministic assessment, calculated indexes from probabilistic assessment at 95% confidence level are also depicted in Figure 115.

Table 93: Deterministic Performance and Process Indexes

Plan	Performance Metric	Target	Estimated Value	Performance Index	Process Index
1	Range	2950 nmi	2950 nmi	1.008	1.000
	Gross Weight	169,000 lb	166,154.3 lb		
2	Range	2950 nmi	2950 nmi	1.011	0.836
	Gross Weight	169,000 lb	165,396.1 lb		
3	Range	2950 nmi	2950 nmi	1.008	0.937
	Gross Weight	169,000 lb	166,154.3 lb		
4	Range	2950 nmi	2950 nmi	1.011	0.899
	Gross Weight	169,000 lb	165,396.1 lb		

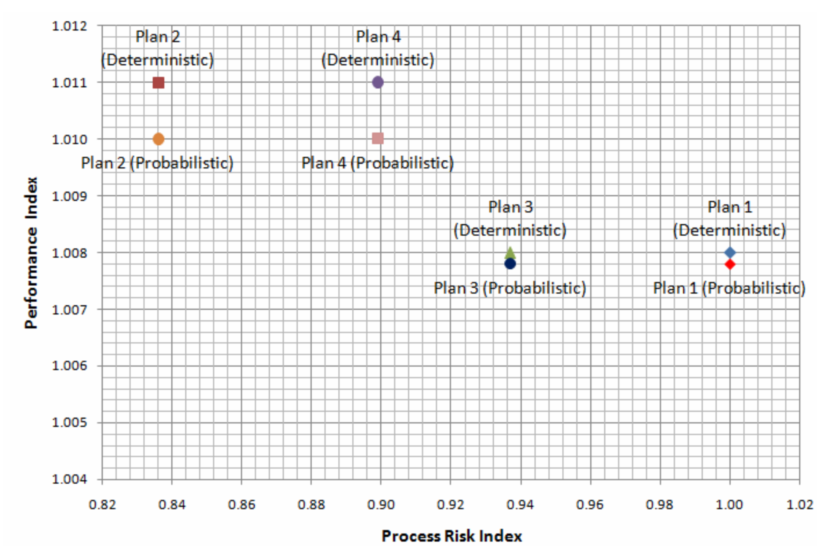


Figure 115: Performance-Risk Plot for Sample Case Study 2

It can be concluded that both deterministic and probabilistic change impact assessments point to the same conclusion for this sample case study. All change alternative plans have a performance index that is above 1. This is an encouraging situation, indicating that they can potentially meet all driving requirements; which is supported by the tabulated data in Table 93. Among them, plan 2 appears to have the lowest risk for its redesign process and shares the best performance index with plan 4. Thus it can be perceived as the best way to redesign the notional aircraft system to satisfy the formulated requirements. On the other hand, plan 4 can be a back-up redesign plan if for some reasons plan 2 is rejected during formal engineering change management process adopted in the company. With available back-up plans, designers do not need to start redesign process from scratch and this can save overall development time.

5.3.6 Conclusion from Case Study 2

This second case study is intended to highlight the overall range of procedures within the proposed SPEC method. Though a complete aircraft system model that is representative of an existing one is difficult to be precisely built with limited data in public domain, the constructed notional aircraft model in this sample case study is believed to be appropriate in capturing the essences of complexity in actual aircraft redesign process. Results from this case study can thus be applied to demonstrate following research hypotheses.

Hypothesis 2 for this thesis study is re-presented in Figure 116. It puts forward the notion that change effects propagation can be effectively managed and controlled through proper assignment of component change role. In this second case study, this condition has been shown and manipulated during the third step of the proposed SPEC methodology.

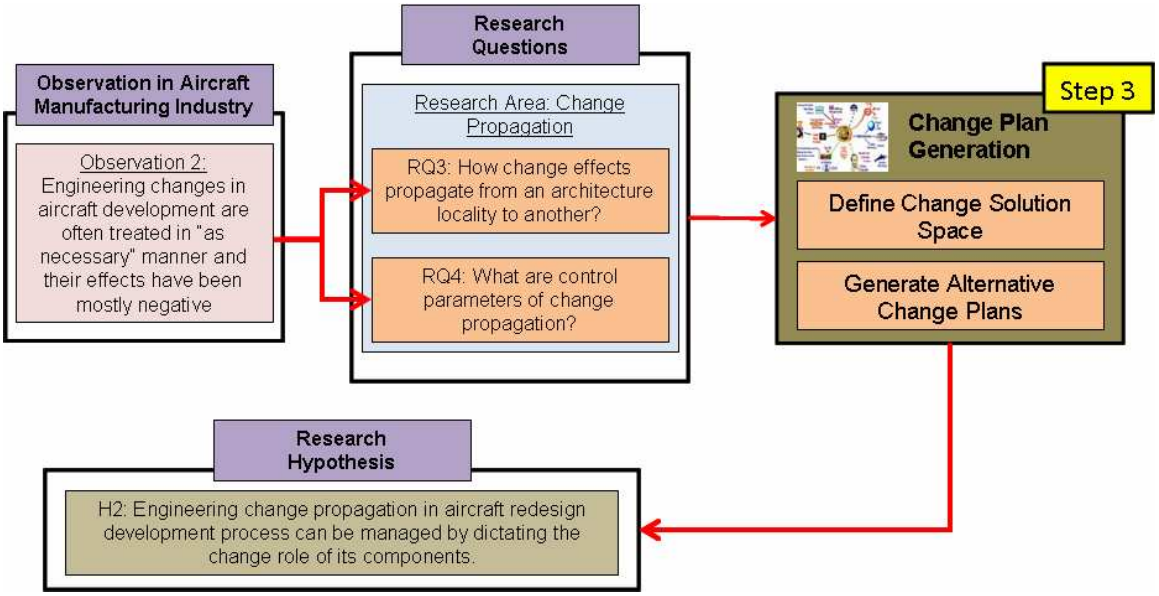


Figure 116: Step 3 and Hypothesis 2

During third step of the case study, components of several aircraft subsystems have been designated as "constants", which indicates that they are not allowed to be affected by the change effects. While generating possible change implementation alternative plans, this "constraint" has its effects on controlling the change effects propagation paths. Consider the potential change effects propagation paths due to modification of IFE control unit to accommodate the new context-aware entertainment system as shown in Figure 117.

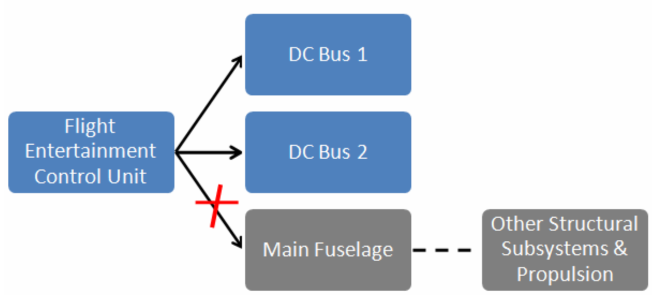


Figure 117: Effect of Component's Change Role in Change Effects Propagation

Because fuselage has been designated as a "constant" in the change solution space, all its main components are not allowed to change. Subsequent to this decision, possible change propagation from IFE control unit to the fuselage with regards to its onboard volumetric space increase is not permitted. By axing this potential change propagation path, other subsystems such as wing and propulsion system are spared from being affected since they are very likely to require modification if the fuselage structure is altered. This observation supports the idea put forth by hypothesis 2, which indicates that it is possible to manage change propagation paths by controlling the assignment of component change roles. With this knowledge, designers can effectively define their solution space and generate change plan alternatives that will not violate their solution boundaries.

On the other hand, hypothesis 3 is related to first step of proposed SPEC method where aircraft system change model is being constructed. Based on literature review study, there appears to be a reasonable concern with regards to finding the right balance between level of details for the model and required amount of efforts for its construction. With tighter budget and development timeframe than original product development, designers cannot afford to allocate too much time for redesign planning. However, failure to identify the right change effects propagation can also be detrimental to the overall process. As evident in helicopter design process in Westland Helicopters Company, about 50% of their total helicopter modifications were overlooked during initial change assessment stage and had to be abruptly handled [81]. Regarding the change model size, Clarkson et al. suggested a change model composition of fewer than 50 components in their method, which is hardly an appropriate size for a complex product system such as an aircraft [80]. Moreover, none of identified product modeling methodologies during the literature review study exercises a formal, standard taxonomy for model construction. This realization leads to hypothesis 3 as presented in Figure 118. In proposed SPEC methodology, the aircraft system change model is tailored to the taxonomy of system element interactions [257] and equipped with supplementary information about its components change tolerance level. Accuracy of the suggested model and its capability to predict change propagation have been demonstrated in the sample case study.

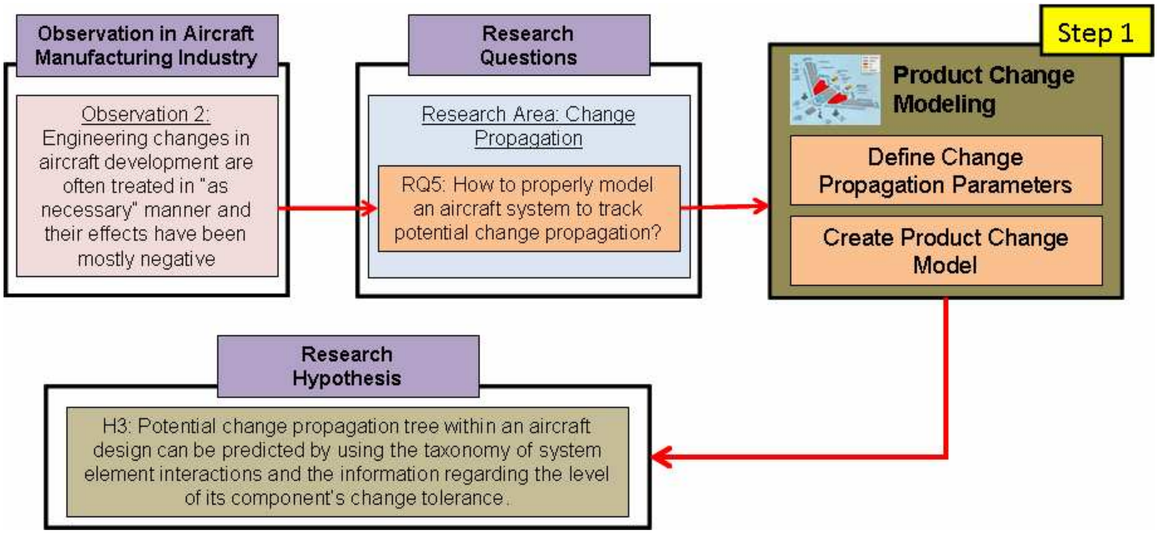


Figure 118: Step 1 and Hypothesis 3

The support for hypothesis 3 is follows. Consider an example case of change propagation for a left air cycle machine unit of air conditioning subsystem. A modification is made on the unit that increases its required electrical power for operation. Using the SPEC support tool, possible propagation paths for any changes made on the air cycle machine unit are shown in Figure 119.

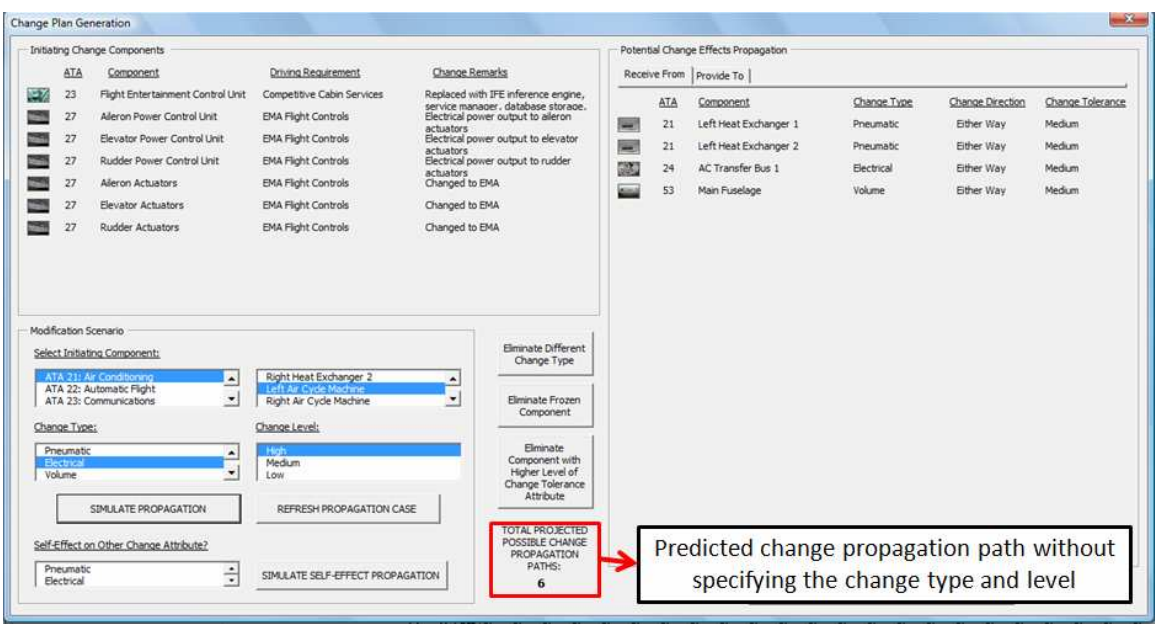


Figure 119: All Possible Change Propagation Paths for Air Cycle Machine

By screening the possible change propagation paths based on their type (i.e. taxonomy of system elements interaction) and modification level, the amount of paths is reduced from six to only one as highlighted in Figure 120. This corresponds to significant reduction in computational efforts for the redesign process and demonstrates possible savings in terms of time and resources when change propagation is correctly predicted. It is concluded that taxonomy of system elements interaction and change tolerance level enables the system change model to be constructed with a manageable size but without sacrificing its level of effectiveness in change propagation prediction. This condition highlights the applicability of the formulated research hypothesis 3.

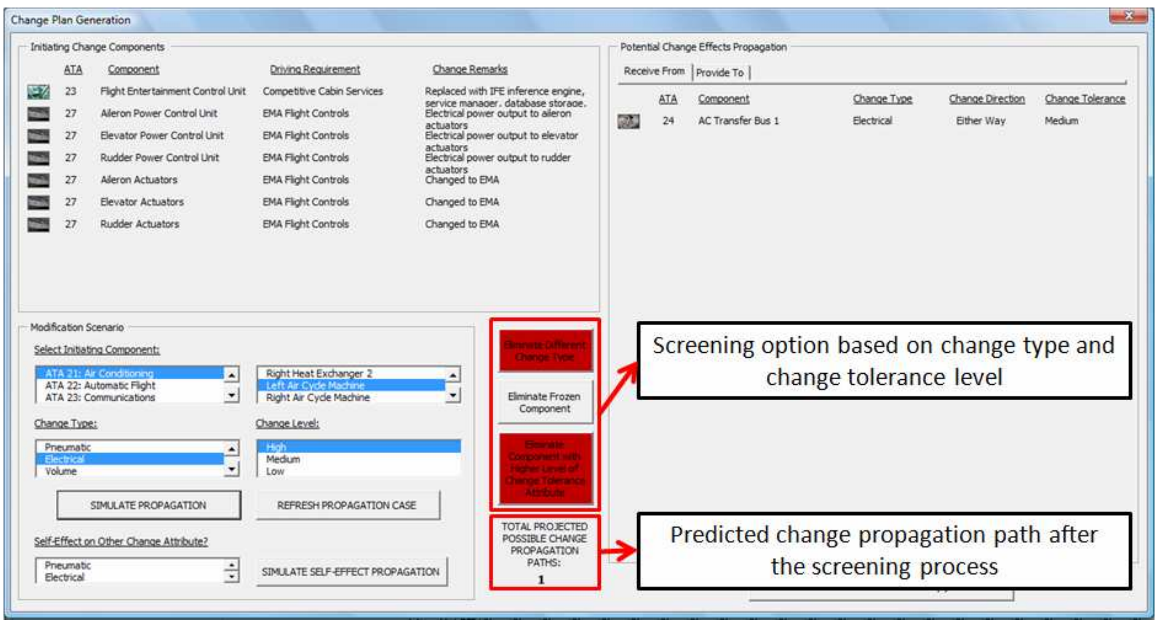


Figure 120: Change Propagation Paths for Air Cycle Machine after Screening

Results of sample implementation case study also demonstrate that the generated change plans correspond to different redesign process risks from each other. Since these change alternative plans are derived by varying the change role of affected components, hence by managing the propagation paths, this can be seen to support the notion of hypothesis 4. Moreover, different change plans also involve different number of affected components. While most available redesign methods seem to focus on minimizing the number affected components to minimize redesign risks, it has been shown from the results of this sample case study that such proposition is not always true. This condition has been emphasized by research hypothesis 5. The ties of research hypotheses 4 and 5 to SPEC methodology can be summarized as depicted in Figure 121.

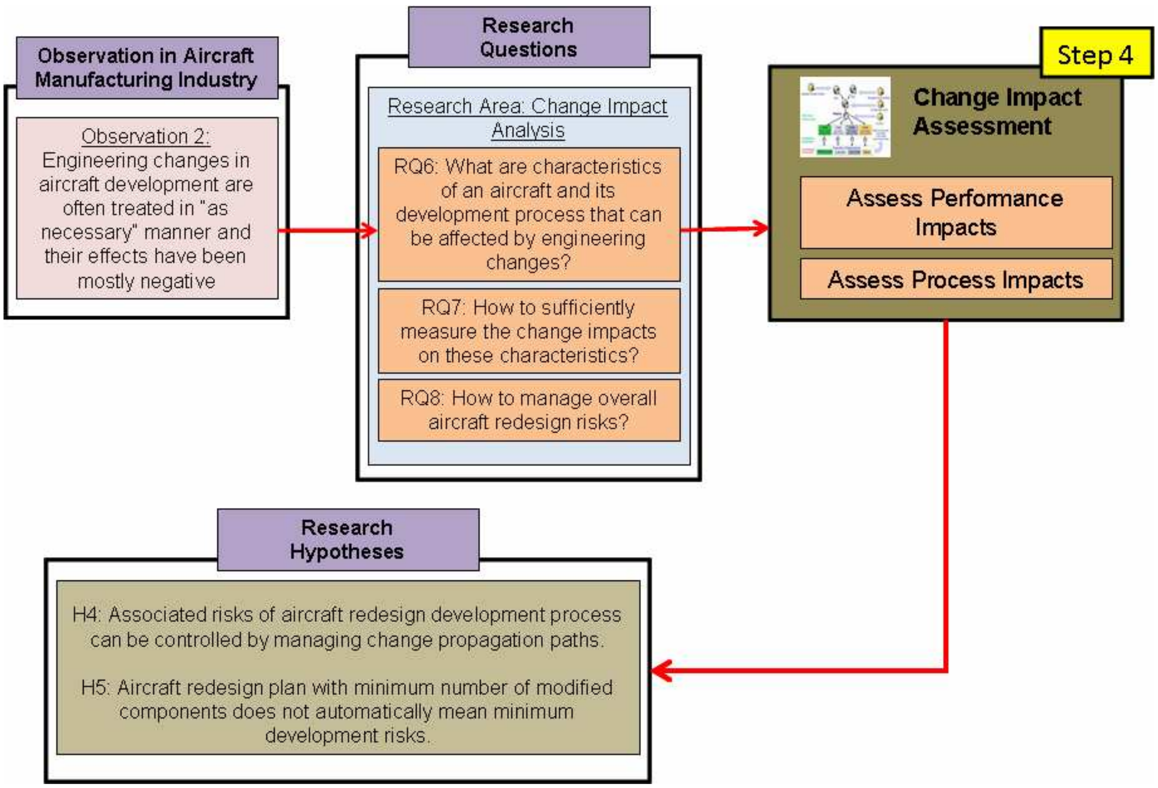


Figure 121: Step 4 and Hypotheses 4 and 5

During change impact assessment in the example case study, the generated change plans have been evaluated with different level of redesign risks. The results are summarized in Figure 122. As indicated, each change plan has a different value of process risk index and this implies that they do not correspond to the same process difficulty. This observation demonstrates the correctness of hypothesis 4 as the change plan alternatives were derived through management of change propagation paths by varying the affected components' change role whenever applicable.

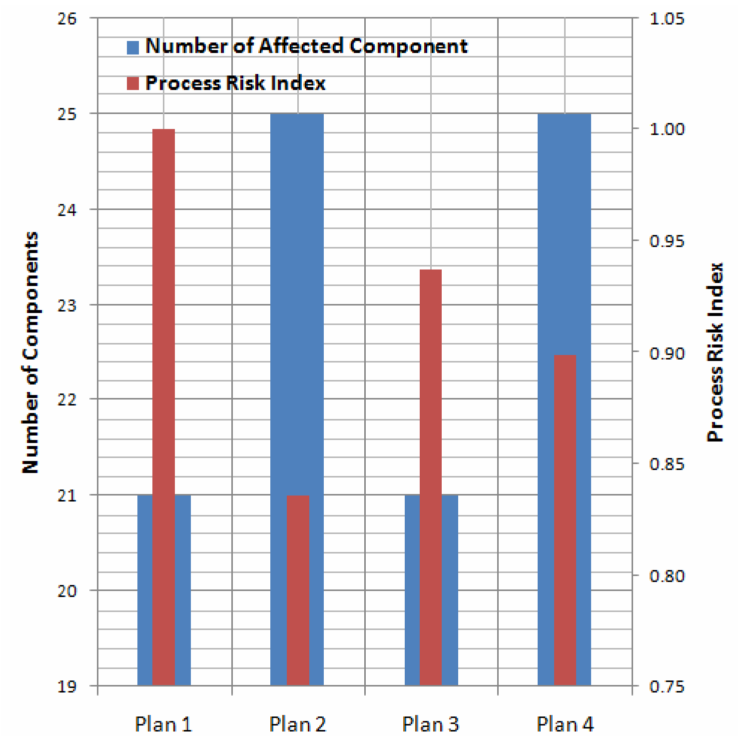


Figure 122: Redesign Risks and Number of Affected Components for Change Plans

In the meantime, the change plans also have different number of affected components but their corresponding risk index value is not exactly proportional to this characteristic. This condition shows the inconsistency of a common proposition that minimum affected parts can guarantee the lowest redesign risks situation. In Figure 122, plan 2 is shown to have the lowest level of redesign process risks but the highest number of affected components. Comparing plan 2 to plan 1, for instance, although plan 1 does not affect the mechanical-based primary flight control inputs mechanism, this decision puts a higher redesign risk on the design of aileron and rudder power control units. They have to be developed with a stable and highly reliable mechanical-to-electrical transducer capability to convert the mechanical inputs into electrical power signals for their EMAs. On the contrary, plan 2 involves replacing the mechanical-based mechanism with direct electrical wirings from cockpit to power control units of the primary flight control surfaces, which is a relatively simpler redesign task that has already been proven to work. This observation supports the notion put forward by hypothesis 5.

Last but not least, hypothesis 6 suggests that the different initiating change requirements should be handled simultaneously. This is different than most available change methods or tools, which tend to favor change planning or analysis per case basis. It is known that some modifications can induced conflicting change impacts on the same components. The ties of research hypotheses 6 to SPEC method are depicted in Figure 123.

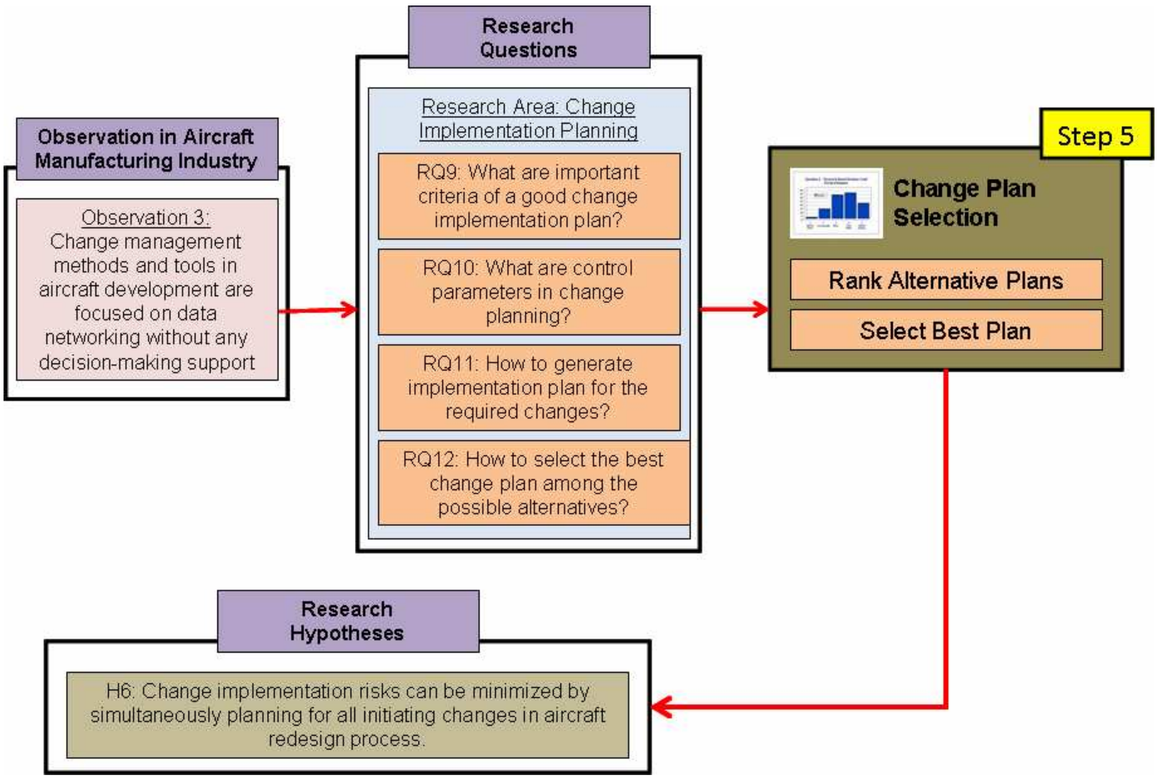


Figure 123: Step 5 and Hypothesis 6

Situation of potential change conflicts have been demonstrated in the sample case study. While considering the redesign tasks for IFE control unit and EMA, change propagation paths from both initiating system changes pass through electrical power distribution and generation components. This is shown in Figure 124 for a better description of the change circumstances.

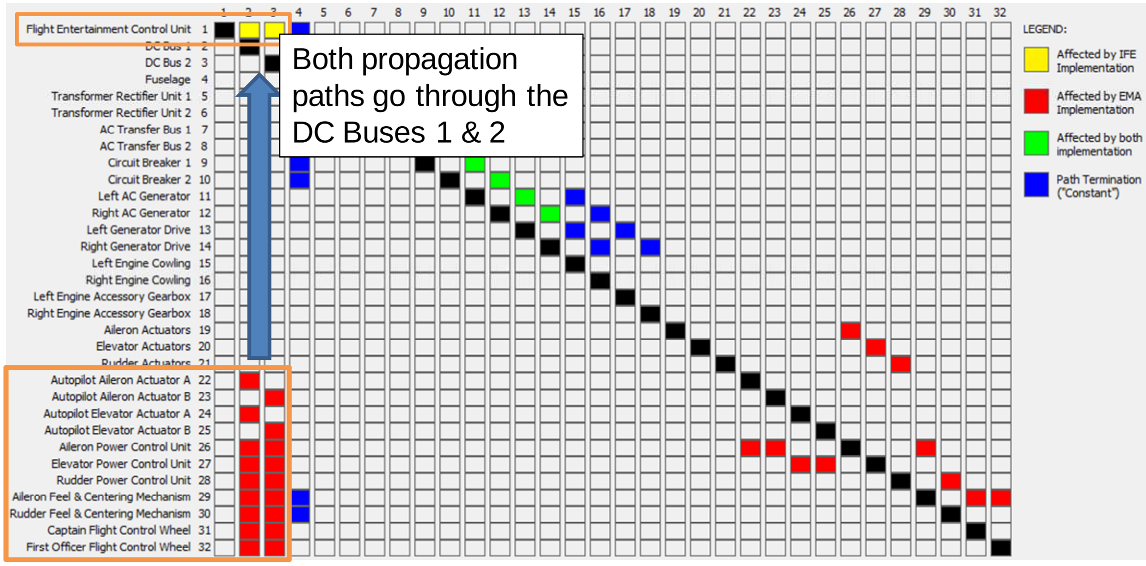


Figure 124: Projected Conflicting Change Propagation Paths for Sample Case Study

If change implementation of context-aware IFE system and EMA are separately planned, it is highly possible that the components of electrical power distribution and generation have to be redesigned more than once. This is because the required power supply increase from both implementations are considered separately and any conflicting or mismatched redesign requirements for electrical power subsystem are usually only recognized during later redesign stages. Once this problem is identified, another round of redesign planning is required. However, if both changes are simultaneously considered from the beginning, these conflicts can be recognized and resolved during the first redesign planning cycle. Though the complexity of the redesign planning process usually increases tremendously by considering simultaneous initiating design changes, its offered benefit of not having to reiterate the whole redesign cycle can be taken to outweigh the increase in computational difficulty. By avoiding the need to reiterate the entire redesign cycle, the process risks are also reduced. This realization effectively supports hypothesis 6.

In summary, results of this sample case study help to demonstrate the formulated research hypotheses for this thesis study.

5.4 Contributions of the Proposed SPEC Methodology

The intellectual contributions that are presented in this thesis study have been introduced in the first two chapters of this thesis but thus far, they have been realized throughout the research works without a proper mention. Recall that the main purpose of this research is to develop a methodology that supports designers in making their decisions regarding the planning of their aircraft redesign. In view of that, this section intends to highlight and discuss the values of contributions from the proposed SPEC methodology in addressing the identified challenges in aircraft redesign planning process. To summarize, primary contributions of this proposed SPEC methodology are listed as follow:

1. **A decision-making aid for aircraft redesign planning**
2. **A structured baseline assessment and selection scheme**
3. **A structured method to define change solution space**
4. **A structured and unbiased analysis of redesign risks**

5.4.1 Decision-making Aid for Aircraft Redesign

As discussed in Chapter 1 and Chapter 2, the prominence of aircraft redesign process is gaining momentum with the shift towards a customer-driven market environment. The rise of redesign approaches has led to the increase of engineering change volumes during product development process but this subject has been relatively under-researched [174]. Most redesign process is presently executed in "as necessary" manner without a proper strategic planning and the main focus has always been on "damage control" rather than product improvement [30]. This is an unfortunate situation given the potential benefits that could be gained by manufacturers if their derivative development is strategically planned. It has been argued throughout this thesis that if the redesign process is correctly approached, the change effects can be appreciably minimized and competitive advantages of the resultant derivative design can also be maximized.

Without proper assistance from change support methods or tools, aircraft designers have to manually plan the whole redesign process based on their past experiences. In many instances, they tend to follow available methods that are meant for original development [104] and this often results in overlooked change effects that have to be unexpectedly handled in late development stages. A case study in Westland Helicopters showed that about 50% of their total helicopter modifications were overlooked during initial change assessment stage and had to be abruptly handled [81]. Since redesign strategy is common in aircraft manufacturing, the utmost advantage is obtained by the fastest manufacturers to develop their range of aircraft options without making any costly errors. This relates to the current “Better, Faster, Cheaper” goal in aerospace industry [239], which stresses on redesign planning efficiency.

Moreover, the capability of aircraft manufacturers to address change requests from their customer airlines as early as during their negotiation process is important for their market competitiveness [268]. The same study in Westland Helicopters showed that 10% to 15% of their helicopter redesign costs occurred before the sales contract was signed and it was used for planning required design changes and predicting their effects [81]. This insight puts a big emphasis on the efficiency of redesign planning, which can only be achieved if the engineering change process is executed in good synergy with the aircraft development process. It has been suggested that no ready-to-use software package that fully supports all aspects of change management process is currently available [259] and this is a key absence considering its prominence in today’s market.

To compare the foundation of available redesign methods and tools with the basis for the proposed SPEC method, one can ask this question: how the process of implementing the required modification on the aircraft design is approached? For many available methods, this situation is coped by simply applying the modification and implementing subsequent changes that are required for its accommodation. Every projected design change is taken as necessary and they are implemented in an “as necessary” manner. But there is another key question to aircraft designers during their redesign planning process: what is the best way to implement the required changes such that the process risks are minimized and the competitiveness of the resultant derivative is maximized? The answer to this question is the groundwork for the proposed SPEC method. Having said that, the key contribution of this proposed method is the offered capability to designers to properly and structurally plan the implementation of any required aircraft design changes with the goal of having a minimum development risk, yet still has a competitive product for the market.

A major difference that sets this proposed redesign method apart from the available ones is how it treats engineering changes. Instead of perceiving all predicted design changes as necessary, the change roles of affected components in the propagation paths are varied to derive alternative redesign scenarios that could potentially be of different risks level. By exploring the full extent of the specified change solution space, the best redesign plan can be efficiently and effectively identified. These differences have been indirectly discussed through comparison of the SPEC method with existing redesign and engineering change methods in section 4.4. As demonstrated by the second sample case study, several change implementation plans can be derived for the same set of required modifications. Because they often correspond to different risks level to each other, the best implementation plan could be overlooked if no thorough redesign assessment is made during planning. In the same case study, it is shown that “one-at-a-time” redesign approach that is reminiscent of typical “as necessary” manner often results in an overworked redesign plan. Due to this situation, it often ends up being less efficient and less competitive, not to mention costly. In contrast, by strategically plan the required change implementation, development risks are minimized while producing a competitive derivative design that satisfies the driving requirements. This capability is the main contribution and advantage that is offered by the proposed SPEC methodology for aircraft redesign process.

In accomplishing this goal, several process elements in the proposed SPEC method also stand out on their own as a significant contribution within their application scope. Their individual advantages are worth mentioning and they are discussed in following sections.

5.4.2 Baseline Assessment and Selection Scheme

Redesign process takes place against the rich background of knowledge and experience that is embodied within the current design, which is the starting point for change process [109]. According to EIA649 Standard, the baseline design acts as a known configuration basis to which any proposed modification is being addressed and planned [297], and this supports the notion that the state of product architecture will influence how the required engineering change can be implemented into it [332]. One of the identified drawbacks for current redesign practices lies in baseline selection process, which is always either taken too lightly or focused solely on existing design capabilities. At present, baseline designs are mostly chosen based on the proximity of their capabilities to the target requirements or simply because they are the natural choice for incremental progression in the product family [105].

As demonstrated by the first sample case study, sole focus on design performances might not completely reflect the suitability of a baseline candidate with regards to the required design reworks. Such high-level approach does not consider the existing state of baseline architecture. Working with existing or finished product designs, even at conceptual level, often comes with less flexibility in terms of the available degree of freedom to implement design changes [115]. This underlines the limitations imposed by baseline design on the redesign approach and the challenges to select the most suitable design for the adaptation or customization tasks [117]. It has been suggested that an effective baseline possesses a highly evolvable design architecture [74]. In support of this idea, Pimmler and Eppinger emphasized on choosing the baseline based on its capability to be modified [257]. Taking this argument into account, it appears that the typical baseline selection for redesign lacks consideration of design architecture influences on complexity and competitiveness of the development approach. It is projected in a product study that 80% of the total design and manufacturing cost for the development process is dictated by the baseline choice [343]. In view of this, the selection procedure should also consider redesign cost-effectiveness and required amount of reworks [178].

In the proposed SPEC methodology, baseline assessment is done through the evaluation of system evolvability metrics as defined in Table 59. This assessment scheme, which is derived based on quantitative system evolvability and MAAP methods, enables designers to not only assess the redesign suitability of a baseline candidate from the viewpoint of its current performances but also the aptness of its existing design architecture. This offers a balanced measurement of baseline suitability with respect to the actual redesign tasks at hand. Moreover, weighting scenario for the evolvability metrics can be varied to match the underlying preference of manufacturers in pursuing their derivative aircraft process. Instead of focusing only high system-level performance evaluation like most available methods, this scheme is more reflective of the redesign development characteristics.

Overall, this baseline assessment procedure aids designers in choosing the best baseline design for the redesign process and in evaluating whether the estimated redesign risks can be competitively justified. In view of the latter condition, redesign development approach has to be more cost-effective than building a new product for similar purpose [74]. The offered capability for designers to either select the best baseline design for the redesign tasks or evaluate the appropriateness of the redesign development risks is an advantage that is not available in any of the identified redesign methods. A good baseline is vital in having an efficient redesign process and the offered capability by the proposed baseline assessment scheme has been highlighted in the first case study.

5.4.3 Definition of Change Solution Space

The planning process for the required change implementation into its baseline design can be an overwhelming task, especially when the design complexity is high and the amount of initiating changes is abundant. As suggested in reference literatures, estimated change propagation paths in a product is a factorial function of its elements [134], which can be extremely high for complex products such as aircraft. Due to numerous possible change propagation paths, tremendous amount of time and efforts is usually required to generate all possible change plans. This situation can reduce the competitiveness of the redesign process, which is often constrained by limited development timeframe and lower budgets and resources than those allocated for new product development.

Many available change methods and tools try to address this issue by simplifying their change propagation algorithm. The original CPM method, for instance, effectively limits its prediction of change effects propagation to only three or four steps after the initiating component [80]. This simplification is made based on the assumption that the probability of change rapidly decreases with each propagation step and becomes too insignificant to be considered. On the other hand, the Monte-Carlo version of CPM further simplifies the propagation path tracking by assuming change propagation likelihood from any product component to be mutually exclusive. This turns the change propagation problem into a series of "random walk". It is concluded that this assumption does not significantly affect the analysis results in comparison to the original CPM and they are achieved with much less computational time [175]. However, these assumptions are still a main concern since they do not represent real practices in the industry and are in great conflicts with the true characteristics of change propagation phenomenon.

At this point, one might ask if there is a proper way to reduce the required computational efforts in redesign planning while still maintain the process integrity with regards to real industrial practices and change propagation phenomenon. In the proposed SPEC method, this issue is tackled by taking advantage of industrial trend in product redesign process. In general, the available change solution space for redesign planning is governed by the change roles for each of the product components. Some subsystems are not allowed to be modified due to company's policy because they cost too much or their adaptation is taken as too risky [115]. During the development of their engine variants, designers in Perkins Engines reserved several parts of the baseline engine from being modified because their redesign was anticipated to cause a significant increase in development efforts and costs [118]. This kind of resolution effectively reduces the potential change propagation paths, hence the possible change plans. Taking this observation into consideration, considerable redesign planning efforts could be saved if designers are assisted with a proper scheme to reduce their product change solution space into a manageable size for the practicality of their redesign analysis. In other words, the redesign planning can be made more efficient if all risky modifications are screened out early in the process. Valuable computational efforts could be saved from being spent on those change plans that would be eventually eliminated regardless.

During redesign planning, designers have a choice to pass on the change effects from one component to another [116]. How a component within the product architecture is affected by the proposed changes will depend on their implementation [81]. The most significant effects on change solution space are made when a component is not allowed to change at any circumstances. As the least risky change implementation plan is preferred, effective change solution space can be derived by “freezing” risky product components from being subjected to any changes by the proposed redesign plan in order to control and reduce the likelihood of further propagated changes [121].

To decide whether a component is risky enough to warrant it to be screened out from the change plans, its evaluation can be made from two aspects of redesign development risks. If the component has a high risk when being changed and at the same time propagates its change effects to other risky components, then it should not be changed. This decision is made to avoid unending change propagation, which has been discussed in section 1.2.2 to be potentially detrimental for the redesign success. However, if the component has been determined as a change initiating component, it should not be designated as a “constant” or otherwise the redesign goals might not be able to be successfully achieved.

In the proposed SPEC method, definition of the change solution space is supported by the measures of change likelihood and change preference for each component. Its application has been demonstrated in the second sample case study, which shows its offered benefits and efficiency in assisting designers to determine a proper solution space for their aircraft redesign planning. Subsequently, the redesign planning efforts can benefit from a better-defined solution space. This enables designers to efficiently explore the available change solution space while keeping their redesign efforts at minimum level.

5.4.4 Redesign Risks Analysis

The most critical phase in engineering change process is change impact evaluation [176]. This can be implied from the emphasis of available standards in manufacturing industries [273]. Before a product change is decided as acceptable, its system-wide effects including the total required efforts for its planning, scheduling and resourcing have to be estimated [152]. A strategic planning decision requires an overall problem outlook since the change effects for the product sub-areas might be connected to each other [334], which depends on applied methods and tools to provide the required information for assessment purposes [211]. The main objective of change impact analysis is to estimate the extent of effects from the proposed product changes, which can help in deciding the most proper redesign plan [170].

Engineering changes can simultaneously affect the product and its development process. It is essential to have proper means to estimate these two types of change effects. In many available change support methods and tools, change impacts are often measured only in terms of process risks. By definition from the risk management field, change risks can be estimated as a product of change likelihood and scale of impacts that it will produce [80, 176]. Few methods include the examination of engineering change effects on the product, especially for complex, multi-level product design structure [160]. It is known that design modification will affect product performance and its exclusion from the change impact analysis should be taken a serious oversight. An incomplete redesign risk assessment can mislead the selection of change plan since it is possible that the plan with the lowest risk level might produce a derivative product that does not satisfy the driving requirements.

In addition, redesign risk evaluation in available change methods and tools often depends on historical product change data. This situation is probably due to the fact that most of them are developed as a data storage system and have limited operational capability. The use of historical data can mislead the conclusion made based on results from the change analysis process since the current change situation and characteristics of the redesign task at hand might significantly differ from those executed in the past.

In summation, there is a need for a change risk analysis scheme that is unbiased and truly representative of redesign task at hand. The analysis should also consider change effects on the derivative product performance. To address this situation, change analysis process in the proposed SPEC methodology refers to the SRL rating scale. This enables a better assessment of change impacts that is not tied to historical change data, which might be outdated or wrongly represent the criteria of present redesign task. The combination of process and performance risks is applied to select the best change implementation, which improves the lack of product consideration in available change methods. As demonstrated in sample case study, this allows designers to have a complete picture with regards to the development risks that are anticipated for the change plan and its effects on the derivative product performance capabilities.

5.5 Chapter Summary

In this chapter, full application range of formulated steps for the proposed SPEC method has been aptly demonstrated. Based on the results from two sample implementation case studies, research hypotheses for this thesis study have been properly demonstrated and validated. This strengthens the case made for the development of this proposed redesign method and supports its applicability within the present aircraft manufacturing industry. Moreover, the new contributions from this proposed SPEC method have been discussed and outlined, which highlight the suggested values of this research work to engineering community in general.

CHAPTER 6

DISCUSSIONS AND CONCLUSION

"*Changes are a vital part for the engineering of successful systems, and it is necessary to understand changes and to have a good grip on them, as the entire product development process can be described as a continuous change management process*."

- Fricke, Gebhard, Negele and Igenbergs (2000)

As outlined in the first chapter of this thesis, the focal point of this research is to develop a methodology that supports the decision-making process in aircraft redesign through an efficient engineering change implementation planning. With the increased prominence of aircraft derivative strategy and the progressively complex aircraft design, redesign tasks become very difficult to be efficiently executed by designers without a proper decision-making aid. The proposed method addresses this growing need that is also recognized by many product companies and academic institutions to be very important in surviving the competitive customer-driven market environment today. Among the reference literatures that also highlight this issue include Eckert, Pulm and Jarratt [117], Rouibah and Caskey [270] and Eckert, Clarkson and Zanker [115].

To support this primary research goal, four major research objectives have been outlined in Chapter 1. They are derived based on observation of industrial practices within general product manufacturing regarding redesign process. These objectives are recalled here as follow.

Research Objective 1: Reduce risks of product redesign process by incorporating changeability assessment on baseline design in early stages

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Research Objective 2: Improve identification of potential change effects by incorporating analysis of direct and indirect change propagation

Research Objective 3: Improve product change implementation planning by aiding designers in defining appropriate change solution space and supporting their change decision-making process

Research Objective 4: Reduce costs and time delays of product redesign process by generating competitive change implementation proposals

Based on these research objectives, the scope of this thesis work is further refined by the observation in present aircraft industry and by the general review on methods and tools available for the redesign process. This is discussed throughout Chapter 1 and Chapter 2, which identifies four main areas of study in the product design field as the current gaps in aircraft redesign process and 12 research questions to address them. The proposed SPEC methodology is developed based on the needs to resolve these redesign gaps. In view of this, literature review of existing methods and tools that could potentially be integrated into the proposed method are presented in Chapter 3. Based on the knowledge of current state-of-the-art methods and tools, six research hypotheses are derived to help answer the governing research questions in Chapter 4. The implementation of the hypotheses and the demonstration of their effectiveness are presented in Chapter 5.

To conclude this thesis study, this chapter is intended to highlight the research work done with regards to the outlined research questions and hypotheses, and to recapitulate their contributions. In addition, several recommendations with regards to future research work based on this study are also discussed.

6.1 Revisiting Research Questions and Hypotheses

Based on the outlined research motivation and the identified research needs in the early chapters of this thesis, research objectives that have to be resolved by this thesis work are established. To accomplish them, several research questions are defined and addressed by the literature study. Based on the knowledge gained from this review, the solution paths for the research questions are supported with the formulated research hypotheses, which are incorporated into the procedures of proposed SPEC method. This section is intended to reflect on the research questions and how they are treated by the hypotheses.

6.1.1 Baseline Assessment

Product redesign process is started with a well-defined baseline [256]. Since the available degree of freedom in planning for the required change implementation is highly dictated and constrained by the choice of baseline, the redesign process has to be managed around its existing design flexibility. Alternatively said, the baseline design governs the available change solution space to satisfy the driving requirements and hence a proper care should be taken while selecting the baseline for redesign approach. To assess whether a baseline candidate is suitable for proposed redesign changes, the criteria of a good baseline design has to be determined. This need is addressed by the first two research questions.

Research Question 1 (RQ1): What are characteristics of a good baseline for aircraft redesign approach?

Research Question 2 (RQ2): How will these characteristics affect the change process?

In section 3.1, some standard definitions for product capability to evolve from its current form have been discussed. It can be implied from reference literatures that the complexity of the redesign procedure can vary from one product to another depending on its design architecture and driving change requirements. Based on this knowledge, it can be inferred that the state of existing aircraft system architecture design has a notable influence on the risk and complexity levels of its required redesign process. This assertion is formalized by the first hypothesis.

Hypothesis 1 (H1): Aircraft design architecture dictates the complexity of its redesign process.

This hypothesis emphasizes the significance of design architecture considerations while selecting the suitable baseline for derivative aircraft approach. So far, most baselines are chosen based on their proximity to the target requirements but their architectural design characteristics also have significant effects on the success of their redesign development.

In Chapter 5, the proposed baseline assessment procedure is applied on three candidates: Airbus A320, Lockheed L-1011 and Boeing B727 based on the formulated design change requirements. From this experiment, it has been shown that the baseline aircraft selection that is based solely on the immediacy of its current capabilities to the requirements does not always result in the best redesign risk conditions. This condition is due to the fact that the amount of required redesign efforts and the cost and difficulty of the process cannot be properly reflected by the high-level aircraft performance characteristics.

6.1.2 Change Propagation

The planning for engineering changes can benefit from a good understanding on how its implementation into the product architecture will affect the other parts. Even for similar aircraft design, there are several ways that the change requirements can be realized. Some trade-offs are involved in deciding whether the change effects should be transmitted to the following component in the propagation tree or not. This also implies that the change impacts, hence the aircraft redesign risks, can be managed by controlling the propagation path. In order to accomplish this, the essential criteria of engineering change propagation need to be well-recognized to enable a better prediction of its likelihood and an accurate assessment of its impacts on the chosen baseline aircraft design. The following research questions are outlined to address this notion.

Research Question 3 (RQ3): How engineering change effects propagate from one architecture locality to another?

Research Question 4 (RQ4): What are control parameters of change propagation?

In section 3.2, relationships between product design elements have been acknowledged as the principal medium for propagation of change effects [109, 116]. Their identification is imperative for a better process coordination during product redesign development [257, 273]. In the reference literatures, change role for the components is observed to vary in different change implementation situations, which correspond to different change effects propagation paths and different level of change impacts. This leads to the belief that the paths of change propagation tree can be controlled and managed by assigning the aircraft components with their preferred change role. This notion is emphasized by the second hypothesis.

Hypothesis 2 (H2): Engineering change propagation in aircraft redesign development process can be managed by dictating the change role of its components.

This hypothesis underlines the influences of component change roles in affecting change effects propagation throughout the aircraft design architecture. By varying their change role within the redesign plan, the change effects can be effectively contained within the preferred architecture locality. In general, the component change roles can be varied as a "constant", "absorber", "multiplier" or "carriers", which have been described in [115].

Through the second implementation case study presented in Chapter 5, it has been shown that different change propagation paths can be derived by varying the change role of main components in the notional aircraft system model. Each propagation scenario corresponds to a different set of affected aircraft components and level of redesign risks. This is due to the fact that each component has different change behavior and hence produces dissimilar change impacts. By comparing different scenarios, the preferred role for the component can be selected in the eventual change proposal plan.

On the other hand, the prediction of change propagation path is often made based on the interrelationships between the components. This indicates that the aircraft change model has to be equipped with proper change information in order to accurately predict potential change propagation paths. Several issues regarding the trade-offs between level of details and required modeling efforts have been prominently raised in reference literatures, apart from accuracy of the modeling technique in capturing the change propagation. This is the main goal for the following fifth research question.

Research Question 5 (RQ5): How to properly model the aircraft system to track potential change propagation?

Based on literature review in section 3.2, engineering change effects are transmitted from one component to another according to their type of interrelationship and level of design change tolerance. Engineering change effects can propagate from one component to the other within the product architecture if and only if there is an interconnection between them [174]. Moreover, if the propagated change effects fall within the component design tolerance, it can absorb them without requiring any modification. These conditions need to be captured by the aircraft change model through proper definition of its parameters. Although many change modeling techniques recognize this need, they do not formally employ a standard taxonomy. This leads to unnecessary information being included into the model and valuable modeling and computational efforts become wasted. A standard modeling guideline is required to control the change model complexity without reducing its competency to predict potential change propagation paths. This notion is reflected in the following third hypothesis.

Hypothesis 3 (H3): Potential change propagation tree within an aircraft design can be predicted by using the taxonomy of system element interactions and the level of its component's change tolerance.

In section 3.5.2, the taxonomy of system element interactions proposed by Pimmler and Eppinger has been considered as the best modeling guideline to capture the prediction of change propagation based on type of component interconnections. Its application with the information of change tolerance level is found to be the best foundation in balancing the details and modeling efforts for the aircraft change model without depreciating its ability to accurately predict potential change propagation paths.

Based on the notional aircraft redesign case study in Chapter 5, it has been shown that the predicted change propagation paths using the taxonomy of system element interactions and the level of component's change tolerance is as good as those made by several other available change modeling, if not better, but with considerably less modeling efforts.

6.1.3 Change Impact Analysis

From the emphasis of many available standards in product manufacturing industries, it can be inferred that the most critical part of change process is its impact evaluation [176]. One of the main difficulties in redesigning a product is to capture its undesirable side effects [247], which often do not only affect the targeted properties but also other product characteristics [314]. To decide whether a proposed change implementation plan is acceptable, its system-wide effects including the required efforts for planning, scheduling and resourcing the redesign development have to be estimated [152]. It is important to have the overall problem outlook while making strategic redesign planning decisions as the change effects for product sub-areas might be connected to each other [334]. The following research questions are outlined to address this issue.

Research Question 6 (RQ6): What are characteristics of aircraft and its development process that can be affected by engineering changes?

Research Question 7 (RQ7): How to sufficiently measure change impacts on these characteristics?

Research Question 8 (RQ8): How to manage overall aircraft redesign risks?

It has been established in reference literatures that engineering changes affect not only the aircraft architecture but also its development process characteristics. It is imperative for designers to be able to distinguish all redesign trade-offs during their decision-making process, especially those with regards to negative change effects. In section 2.1.1, the utmost value for aircraft manufacturers in considering redesign approach is the capability to produce derivative aircraft design that satisfies the new requirements with a cheaper and shorter development process than it will take them to produce a new original aircraft. Although this can also lead to sub-optimal derivative designs, most redesign decisions are often tailored to the estimated risks based on redesign development costs and amount of reworks [116]. In view of this, redesign risks can be related to the affected components and the cumulative handling time, cost and efforts that is required for their modification [167]. This is related back to the management of change propagation paths, which can be controlled in order to manage the overall aircraft redesign risk. The following hypothesis avows this perception.

Hypothesis 4 (H4): Associated risks of aircraft redesign development process can be controlled by managing change propagation paths.

As discussed before, different change propagation paths can have different set of affected components and because they usually have different change behaviors, change effects on different components can vary from each other. This leads to a different level of overall aircraft redesign risk. As stressed by this hypothesis, the redesign risk can be managed by selecting change propagation paths with the lowest overall risk.

From the notional aircraft redesign experiment in Chapter 5, the variation of change risks between potential change plans has been demonstrated. The change implementation plans are effectively derived by varying the possible change propagation paths and this shows the possibility to control redesign risks by controlling change propagation.

Based on the literature review, there is a big misconception that redesign plan with the smallest number of affected components always corresponds to the lowest development risks [344]. For instance, the computer-based change tool by Lin et al. aims to modify a product to meet its new requirements with the minimum number of changes [202]. This perception is rather misleading because the overall product change risks is dependent on the type of required modification and affected components. The following hypothesis is outlined to denounce this notion.

Hypothesis 5 (H5): Aircraft redesign plan with minimum number of modified components does not automatically mean minimum development risks.

As can be observed from the results of the notional aircraft redesign case in Chapter 5, it is clear that the change implementation plan with a small number of affected components does not necessarily correspond to a lower overall redesign risks compared to the change plan with a higher number of modified components.

6.1.4 Change Implementation Planning

At first glance, product redesign process might seem deceptively like a simple task but it often ends up being more complicated once executed. As a tie-in for previous hypotheses and research questions, the knowledge gained so far can be used to select the best aircraft redesign plan among the possible ones. Based on the elements of change implementation process, a good redesign strategy is required to guide the product modification planning. This is the main intention for the following research questions.

Research Question 9 (RQ9): What are important criteria for a good change implementation plan?

Research Question 10 (RQ10): What are control parameters that are available in change planning?

Research Question 11 (RQ11): How to generate implementation plan for required changes?

Research Question 12 (RQ12): How to select the best change implementation plan among possible alternatives?

Redesign risks can be broken into performance and process risks. Performance risk refers to the possibility that the aircraft modification will fail to satisfy performance constraints while process risk covers the likelihood of failure to execute aircraft redesign procedure within the allocated development constraints. These risks can be used as an indicator for the goodness of a redesign plan. In addition, many product redesign cases involve several initiating changes and their effects can be interconnected [67, 174, 218]. Many available methods or tools cope with this situation by planning for the changes separately in order to minimize computational efforts. However, it is acknowledged that their effects can be interrelated [120, 272, 332]. Overlooked interactions between the proposed change plans for different change requirements can cause undesirable change effects that increase the redesign risks when they are implemented into the aircraft. This leads to the notion that a lower redesign risk is possible if all initiating changes are concurrently planned, which is affirmed by the following hypothesis.

Hypothesis 6 (H6): Change implementation risks can be minimized by simultaneous planning of all initiating changes in the aircraft redesign process.

In Chapter 5, the projected redesign risks for change plans that are derived concurrently and separately for all initiating changes have been discussed through the notional aircraft redesign experiment. As emphasized by this hypothesis, change plans that are constructed by considering the change requirements simultaneously tend to have a lower likelihood of requiring iterations and redesign risks.

6.2 Summary of Research Contributions

The main contribution from this thesis research work is the development of the proposed SPEC methodology, which is expected to improve the efficiency and quality of derivative aircraft planning process. By being an effective decision-making support for designers, it helps to guide them in planning for the best possible redesign scenario in accordance to their company's capability. It starts with the assessment of baseline candidates on which the redesign changes will be applied and ends with the selection of the perceptively best plan on how the modification could be realized into the chosen baseline design.

Another main contribution from this thesis is the formulation of the baseline assessment procedure. To fill the identified gaps in baseline selection practices, the proposed process provides a more thorough outlook on suitability of the baseline candidate to undergo the proposed redesign changes. In addition to the focus on the closeness of performances to the target requirements, it allows designers to gain insights about the risks and difficulty level associated with the redesign process if the candidate design is indeed chosen to be the baseline. This is made possible by having the assessment efforts to focus also on the existing system architecture characteristics, which have a big influence on the flexibility to accommodate the suggested changes. With the importance of a suitable baseline, this process helps to reduce the overall complexity and costs of the redesign process.

Furthermore, the definition of change solution space is the third main contribution of this research. By exploiting the general trend of redesign practices in the product industry, the proposed procedure enables designers to efficiently construct the available solution space for their redesign planning process. This allows the full exploration of possible change plan alternatives without wasting costly computational efforts on analyzing plans that will be discarded due to known preferences of the designers' or company's policy. In other words, by having the change solution space defined and mapped out, designers can focus their redesign efforts more efficiently on planning the alternative change plans that have a higher possibility to be selected.

Last but not least, the fourth contribution from this research is the redesign risk analysis procedure. While the traditional change analysis often relies heavily on historical data to measure the level of propagated change impacts and its likelihood, it is suggested that the analysis is based more on the current change scenario at hand. Instead of relying on the past data that can mislead the entire analysis conclusion, the assessment is based on SRL rating scale for the suggested design changes. This is taken to be more representative of the risks involved in the present redesign task. Furthermore, the impact analysis focuses on both the process and product, in which the latter aspect is notably missing from many available change methods and tools. The proposed procedure resolves this situation and allows designers to have a complete picture of the risks involved for each generated alternative change plan. This aids them in making a better change plan selection and also increases their understanding of the overall redesign process situation.

6.3 Avenues of Future Works

From one perspective, the work that has been done in this thesis research can be treated as the beginning of a much larger effort to improve aircraft redesign process, or product redesign process in general. Within this section, several ideas on how the results from this study can be further used in future works are shared.

6.3.1 Extension of Example Problems

The sample problems presented in this dissertation are intentionally made simple, as the main goal here is to demonstrate the capabilities of the proposed SPEC methodology. In view of that, the application of this method on an actual aircraft redesign problem is seen as the natural way forward. To accomplish that, the required inputs into the method have to be established first and among others, these include accurate subsystems model for the baseline candidates and underlying relationships between aircraft component parameters and its system-level metrics.

6.3.2 Exploring New Application Territories

Since there are many interesting factors that are acting as the driving sources for the need of aircraft redesign approach, it is foreseen that this proposed SPEC method can also be applied with several different objectives instead of a redesign planning support tool. For instance, newly available or emerging subsystem technologies are among the drivers for derivative aircraft development but implementing them for certain aircraft components or subsystems is not always a “plug-and-play” matter. Most of the times, implementation of the new technologies require other system modifications that can also point to other new technologies. In view of this, the proposed method can be used as a technology planning support, in which the decision to pursue a new technology can be thoroughly assessed in regards to its impacts on the current aircraft system design due to integration issues and identification of other related technologies that are favorable to be simultaneously pursued for the future development process. Accordingly, the technology implementation into the aircraft system can be made in the most effective manner without having to wait for another cycle of technology development for the other required technologies.

Furthermore, because of its generic nature, the proposed SPEC methodology can also be applied to other product types apart from aircraft system. A slight modification to some of its procedures might be necessary to better match the characteristics of the various product redesign processes but it is not expected to be a huge variation from the one formulated in this study.

6.3.3 Application with Modeling and Simulation Environment

The description of the proposed method indicates that its application can highly benefit from the use with a modeling and simulation environment. Instead of having a static evaluation of aircraft performance metrics based on defined RSEs whenever a subsystem parameter is modified as a result of the proposed redesign changes (as demonstrated in the second implementation case study), a more interactive decision-making environment can be made available if the programmed SPEC support tool is executed in a real-time connection to the aircraft performance analysis tool. This situation is expected to allow a better understanding of the change situation and perhaps improve the screening procedure of the potential change alternative plans for a more efficient change planning process.

6.4 Personal Note

It should be noted that more than half of the efforts involved in realizing this thesis study have been focused on the development of the Excel-based SPEC support tool. Despite the fact that this support tool is not the main objective of this research, it is nevertheless the most essential element that enables the successful demonstration of this proposed SPEC methodology. The reason for this situation is the high level of aircraft design complexity. Although the components for each of its subsystem models have been limited to only 30, the resultant subsystems interrelationship DSM is still very large to be assessed manually. In this case, considering each subsystem has 30 components, the size of overall aircraft DSM model is 1020 x 1020. With such big matrix, the model construction and the change effects propagation tracking are not an easy task to be manually executed. On one hand, this experience further solidifies the belief of the existing urgent need for a better product redesign method and tool to aid designers in planning for changes. On the other hand, the development of SPEC support tool has been limited by the time constraints and the focus on aircraft redesign problem. This means a lot more improvements can be made to better its future execution and application.

Another part of this research that is worth mentioning is the interesting side fields of study that keep presenting themselves throughout this thesis research. Some of them have been incorporated into this study to some extent but due to the high interest of having a manageable research size and scope, several of these areas of study have to be left behind for future exploration. For instance, a more elegant methodology to identify and resolve the potential change propagation conflict between different initiating change paths is an exemplary aspect of product redesign study that is not included. Another example is the redesign trade-offs during product requirements analysis to assist designers in selecting the best possible system modification to satisfy the requirements. The identification of many interesting areas in the product redesign study that have yet to be fully explored supports the notion put forth by Jarratt [174] and Wright [344] that this product redesign field has more to be developed unlike the original product development.

APPENDIX A

FLIGHT ROLL CONTROL MODELS FOR CASE STUDY 1

A.1 Primary Roll Control Mechanism on Airbus A320

Primary flight roll control on Airbus A320 is achieved through the deflection of available aileron surface on each wing. These control surfaces are actuated by electro-hydraulic servojacks and their position is determined through the processed signals from sidestick controllers by elevator and aileron computers. Overall, the schematic of this roll control mechanism is depicted in Figure A.1.

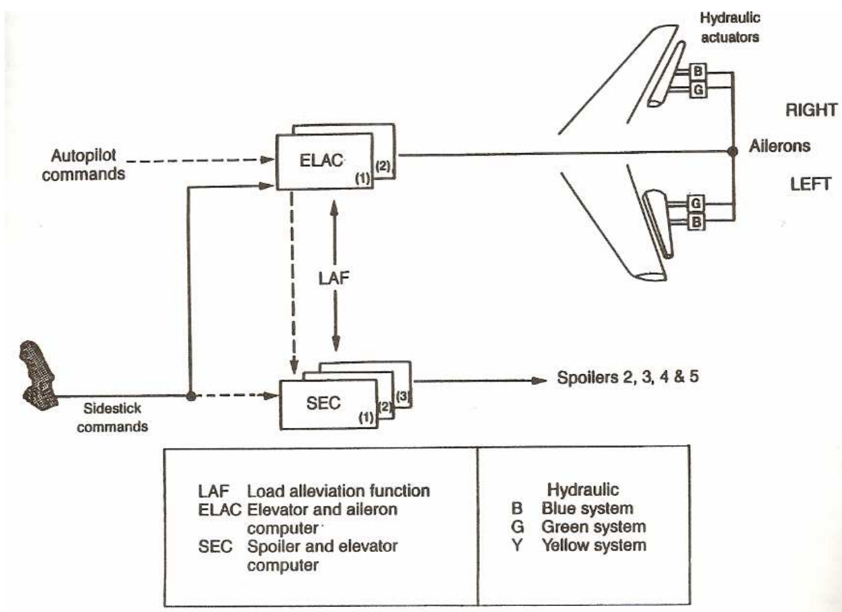

Figure A.1: A320 Roll Control System [338]

The corresponding DSM system change model for this primary roll control mechanism of Airbus A320 aircraft is constructed through physical decomposition process of the above system. This is presented in Figure A.2, which is output from Excel-based SPEC support tool. It should be noted that the modeling process is only focused on primary roll control, which involves position control of aileron surfaces.

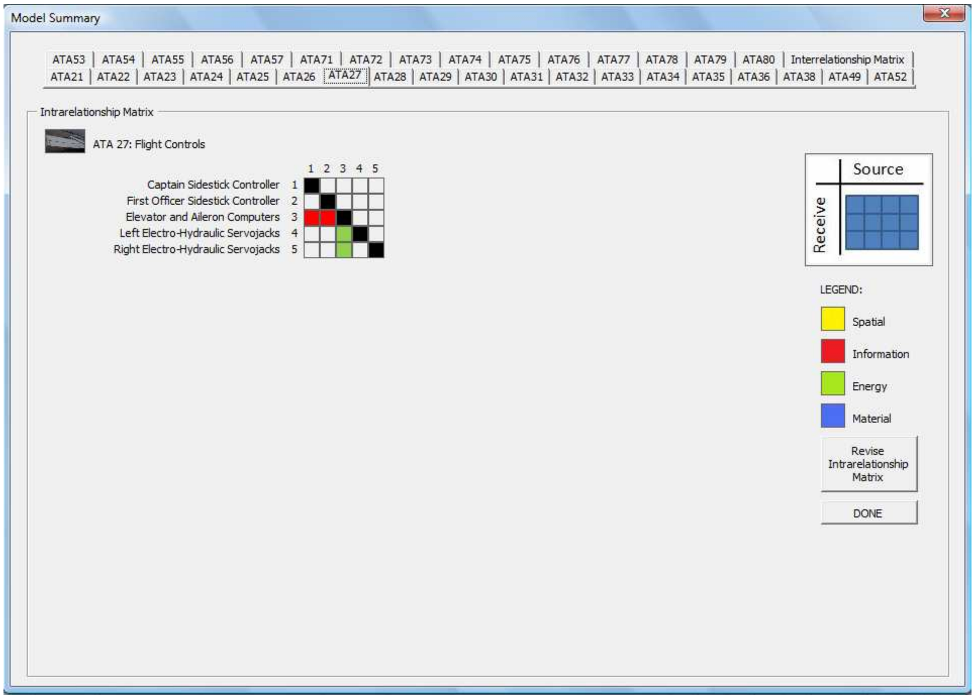

Figure A.2: DSM Change Model for Primary Roll Control of A320 Aircraft

A.2 Primary Roll Control Mechanism on Lockheed L-1011

In Lockheed L-1011 aircraft design, primary flight roll control is achieved by four aileron surfaces and their control mechanism is illustrated in Figure A.3.

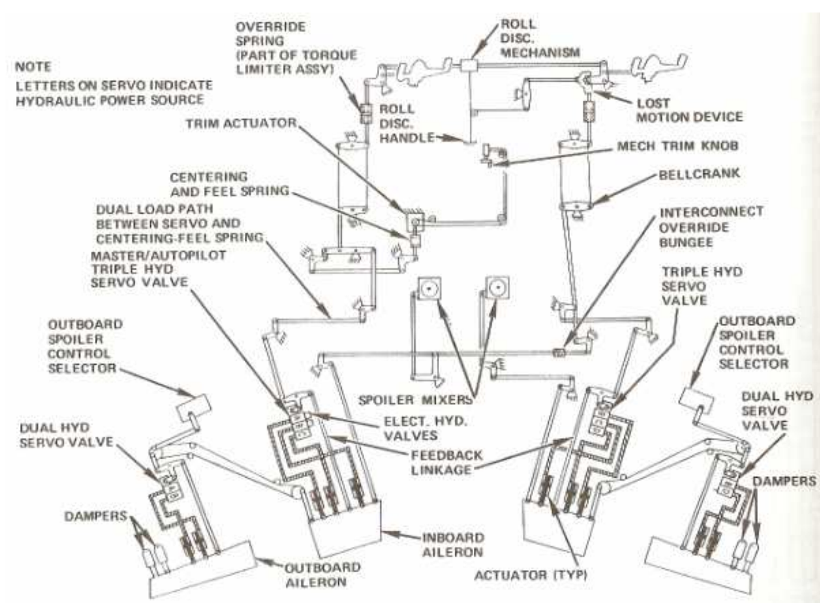

Figure A.3: Lockheed L-1011 Aileron Control System Schematic [338]

In short, control inputs are supplied by the captain or first officer from either one of the control wheels. These inputs are passed through a combination of cables and pushrods to master aileron servo, which is located at left inboard aileron. Through mechanical links, other aileron servos receive their respective positioning inputs from the action of master servo.

The corresponding DSM system change model for primary roll control mechanism of the Lockheed L-1011 aircraft is constructed through physical decomposition process of the above system. This is presented in Figure A.4, which is output from Excel-based SPEC support tool. It should be noted that the modeling process is only focused on primary roll control, which involves position control of the aileron surfaces.

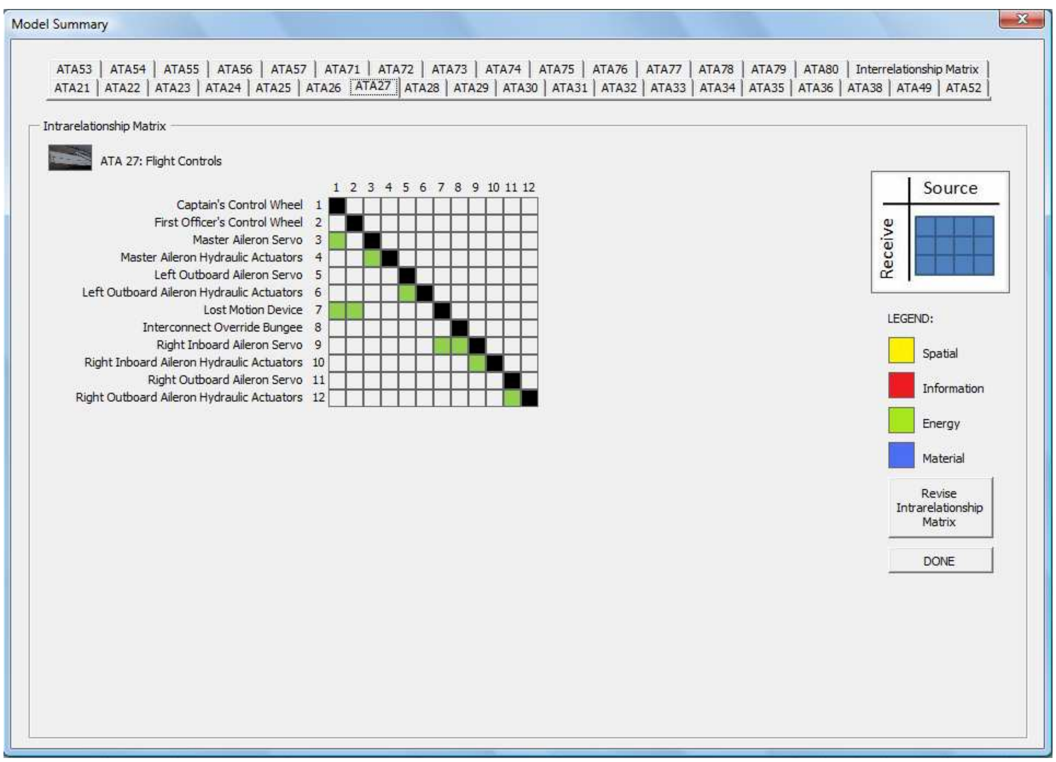

Figure A.4: DSM Change Model for Primary Roll Control of L-1011 Aircraft

A.3 Primary Roll Control Mechanism on Boeing B727

Primary roll control of Boeing B727 aircraft is achieved by the positioning of four aileron surfaces, two for each wing. Control inputs are initiated through either one of the control wheels, which are then mechanically passed to aileron power control unit. In summation, this roll control scheme is depicted in Figure A.5.

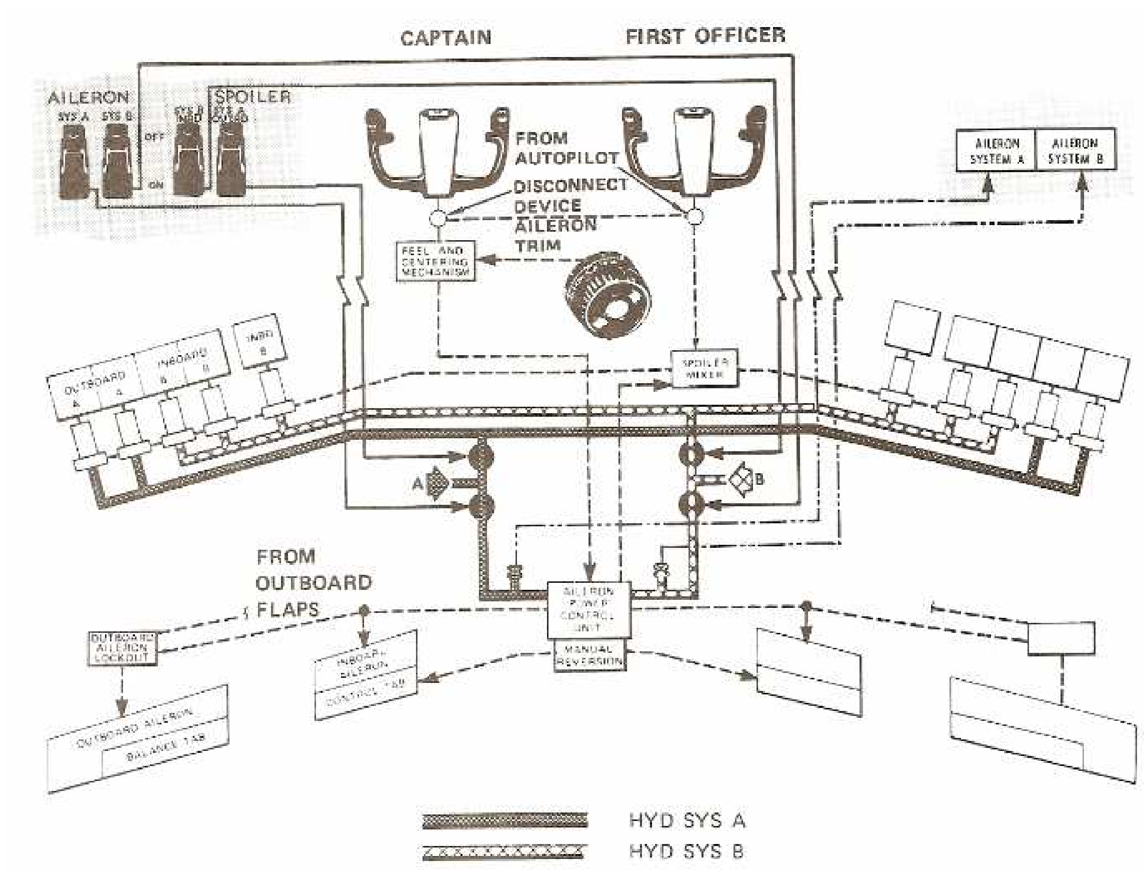

Figure A.5: Roll Control Aileron System on Boeing B727 [338]

The corresponding DSM system change model for primary roll control mechanism of the Boeing B727 aircraft is constructed through physical decomposition of the above system. This is depicted in Figure A.6, which is output from the Excel-based SPEC support tool. Once again, note that the modeling process is only focused on primary roll control, which involves the position control of aileron surfaces.

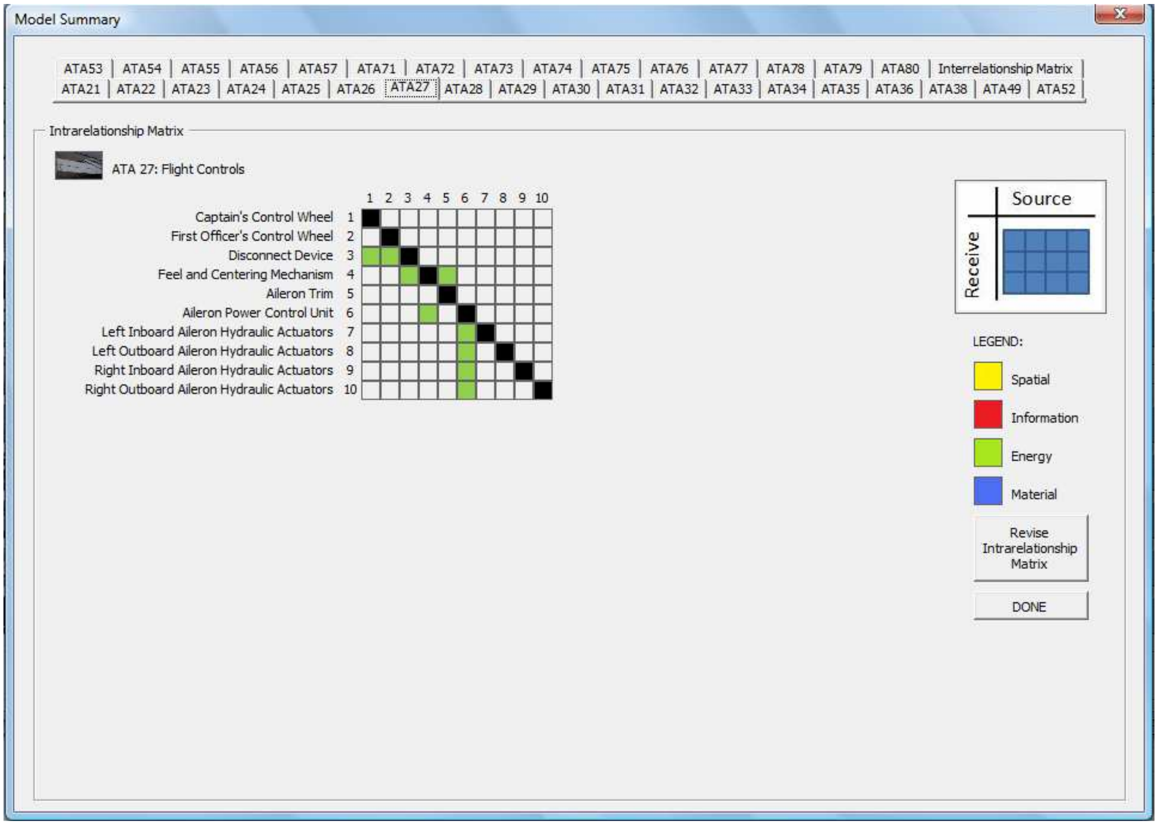

Figure A.6: DSM Change Model for Primary Roll Control of B727 Aircraft

APPENDIX B

AIRCRAFT SUBSYSTEMS MODEL FOR CASE STUDY 2

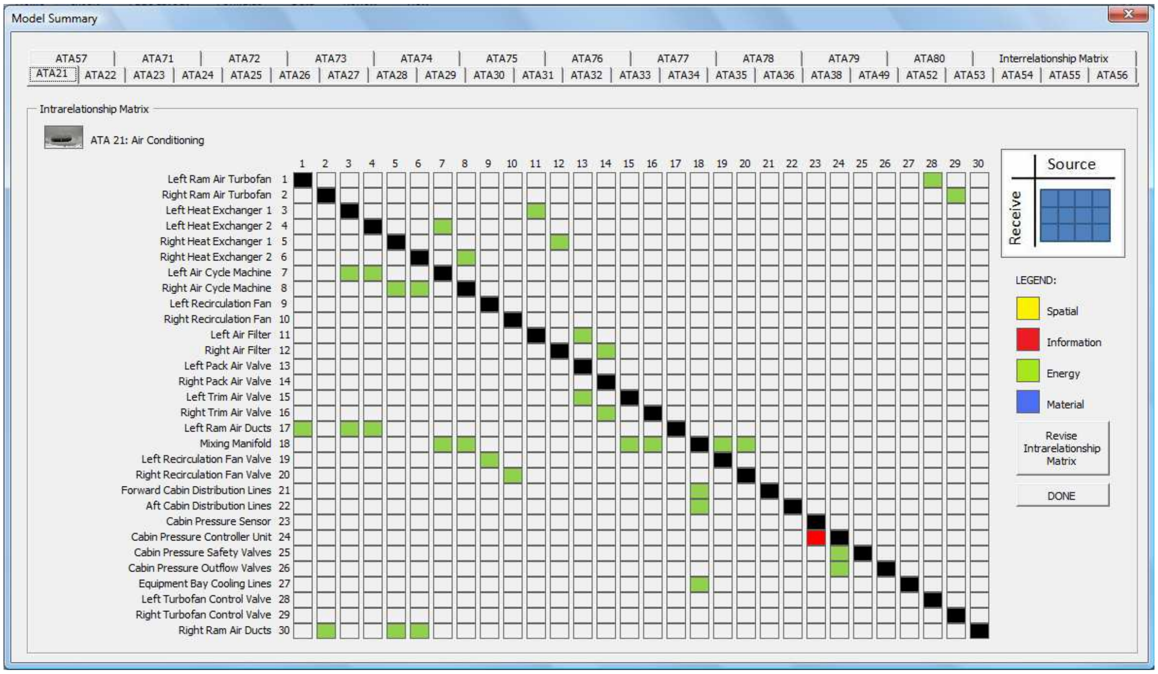

Figure B.1: DSM Model for ATA21 Subsystem of the Notional Aircraft System

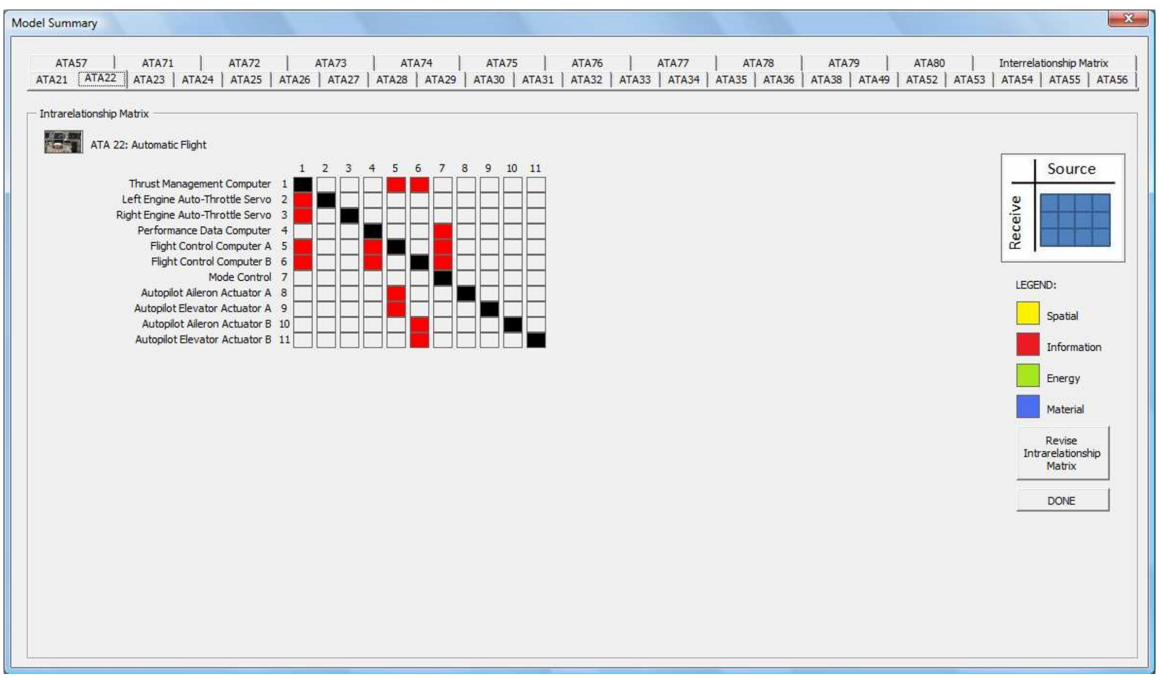

Figure B.2: DSM Model for ATA22 Subsystem of the Notional Aircraft System

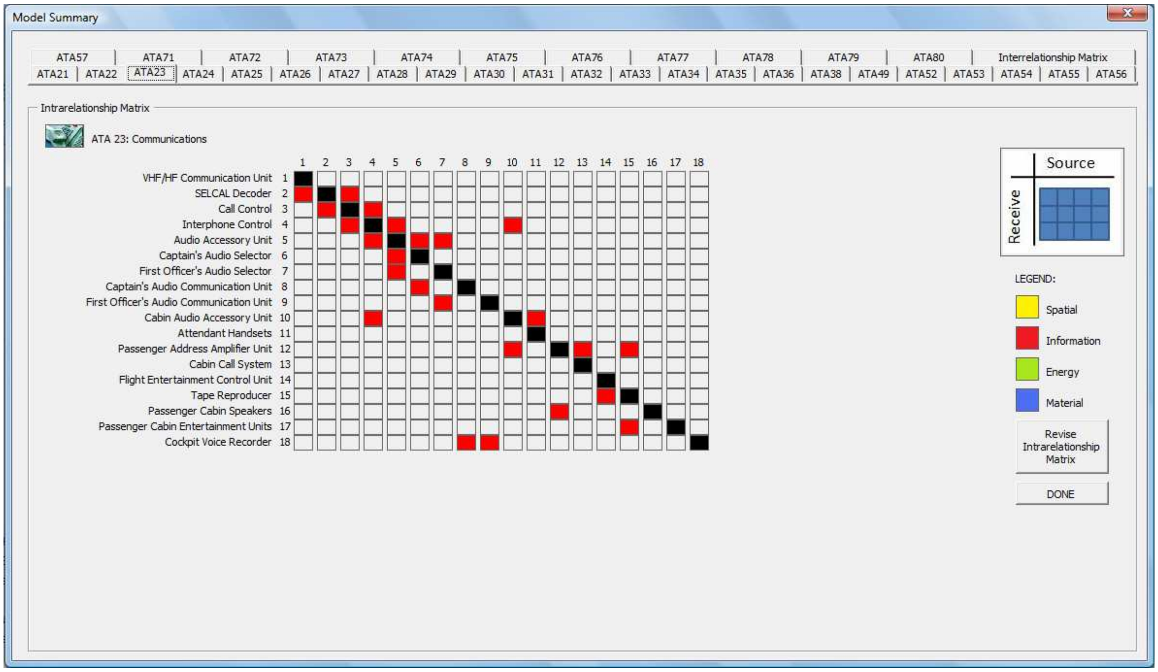

Figure B.3: DSM Model for ATA23 Subsystem of the Notional Aircraft System

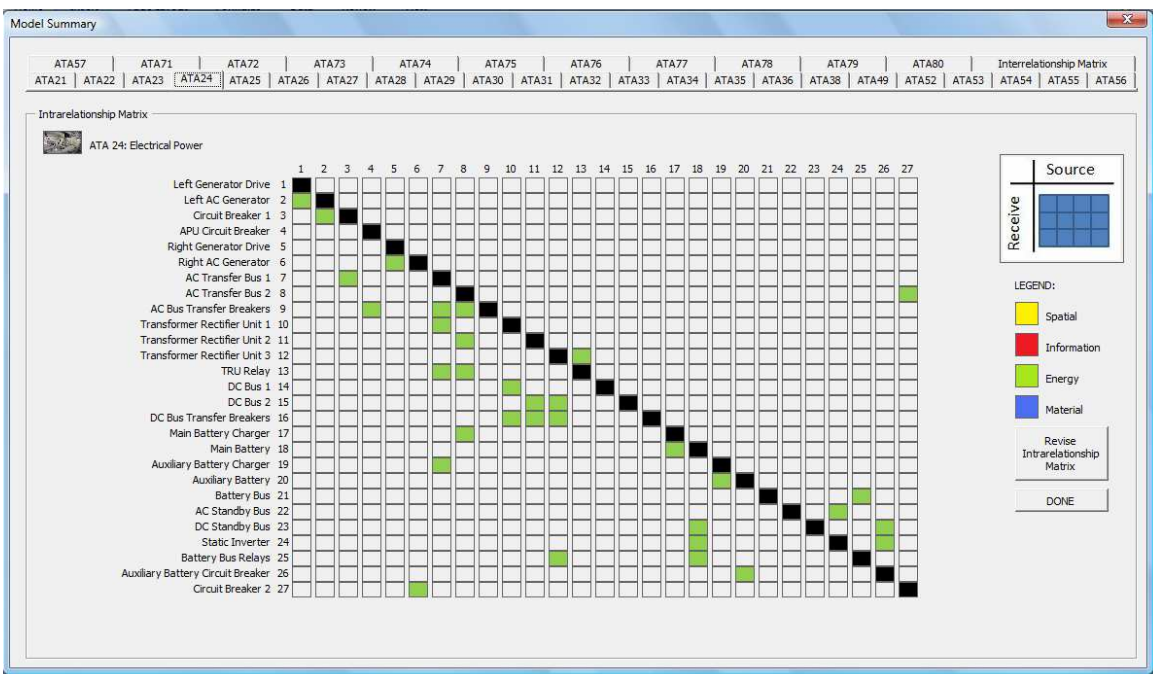

Figure B.4: DSM Model for ATA24 Subsystem of the Notional Aircraft System

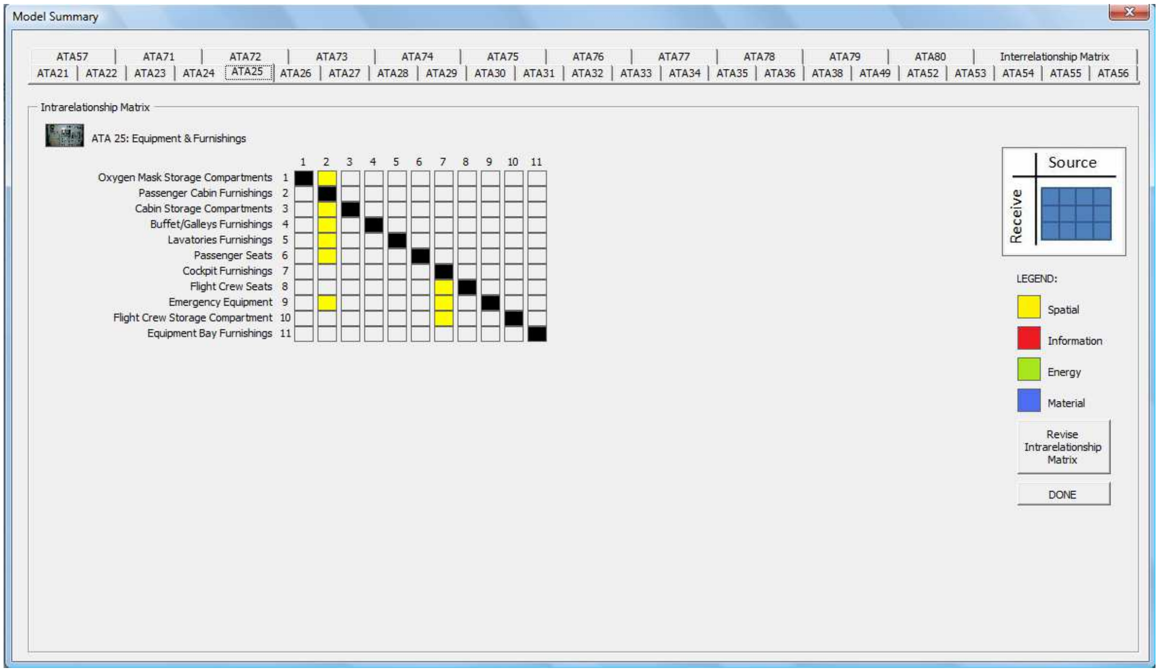

Figure B.5: DSM Model for ATA25 Subsystem of the Notional Aircraft System

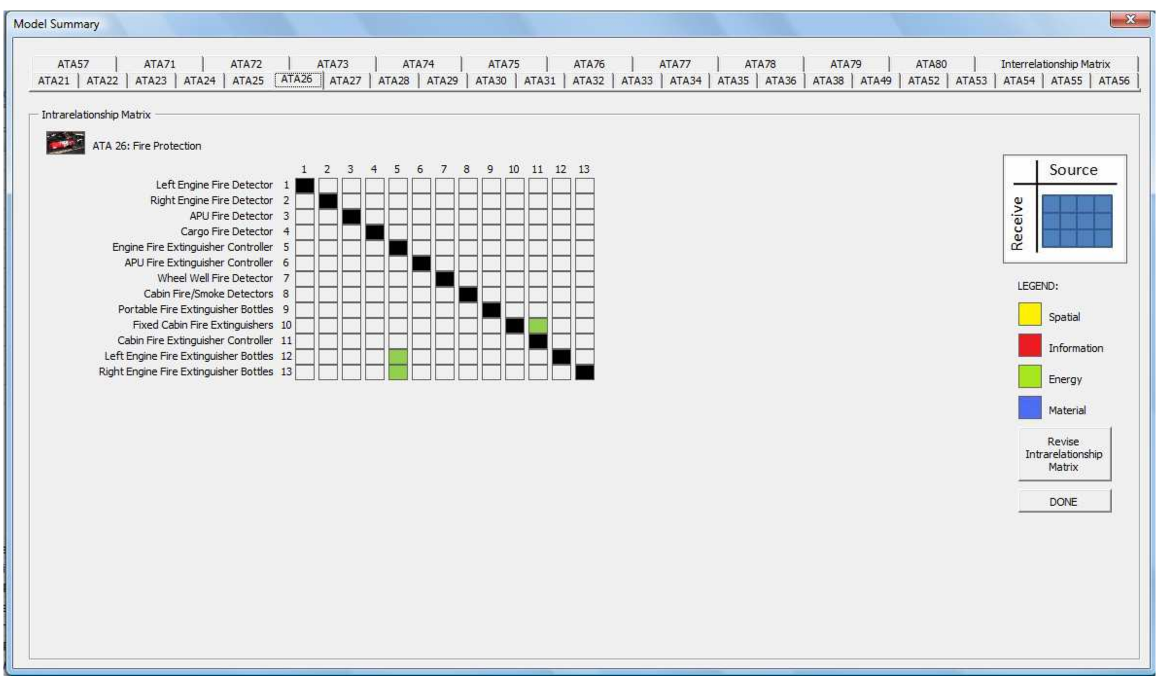

Figure B.6: DSM Model for ATA26 Subsystem of the Notional Aircraft System

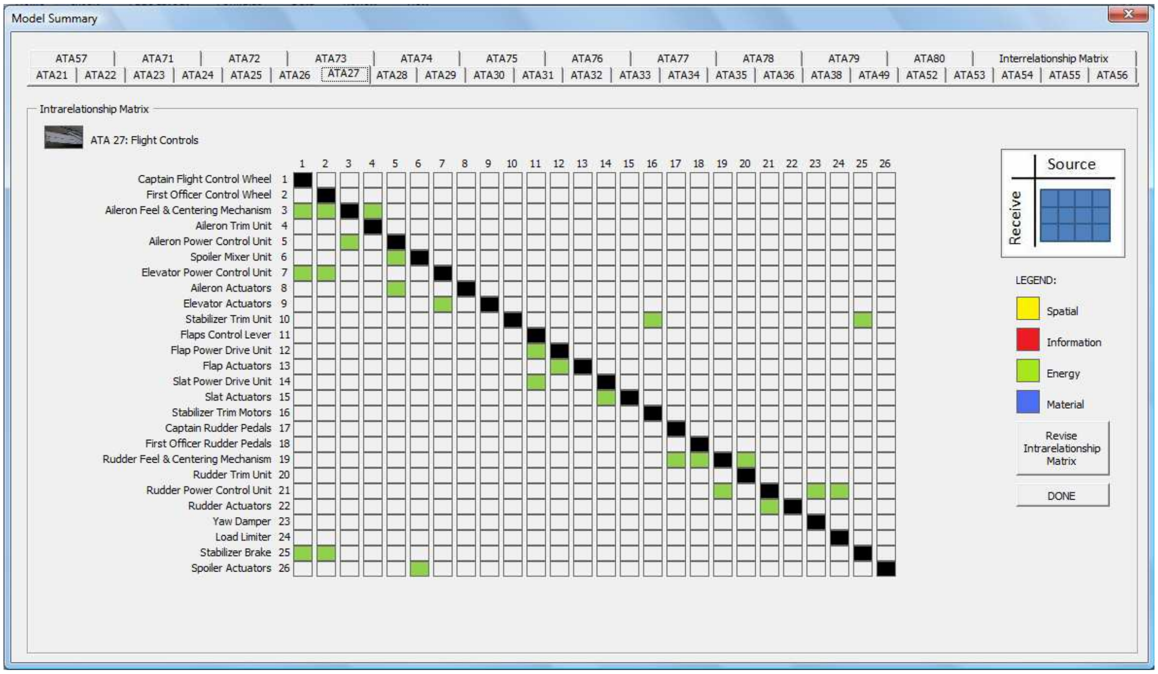

Figure B.7: DSM Model for ATA27 Subsystem of the Notional Aircraft System

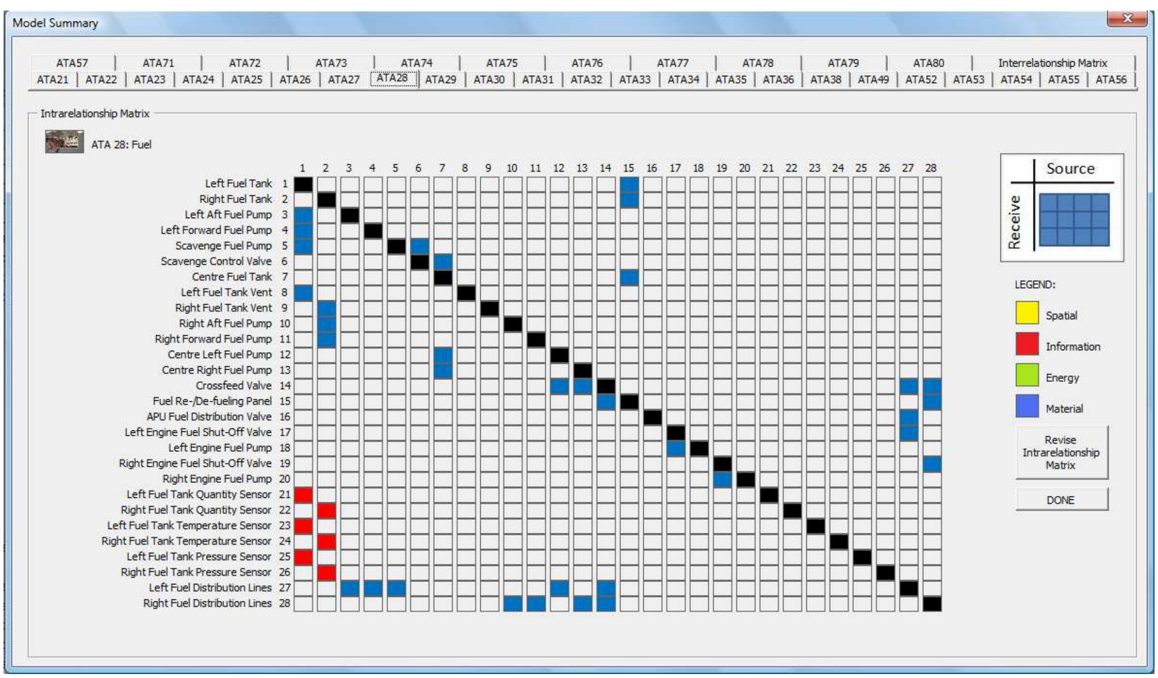

Figure B.8: DSM Model for ATA26 Subsystem of the Notional Aircraft System

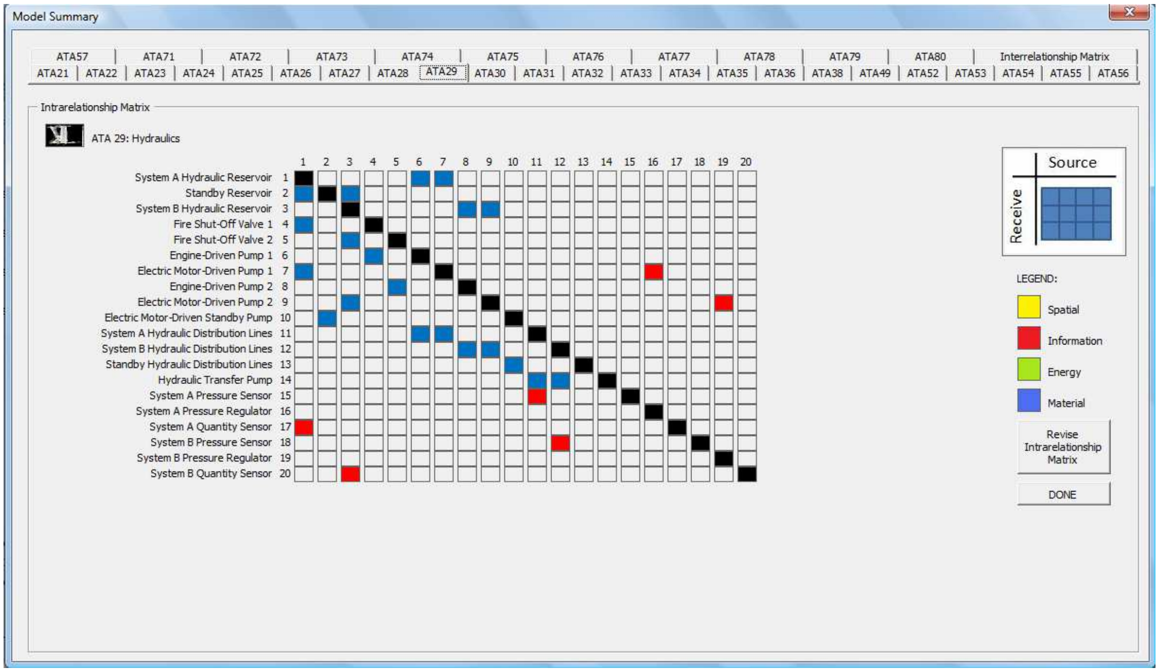

Figure B.9: DSM Model for ATA29 Subsystem of the Notional Aircraft System

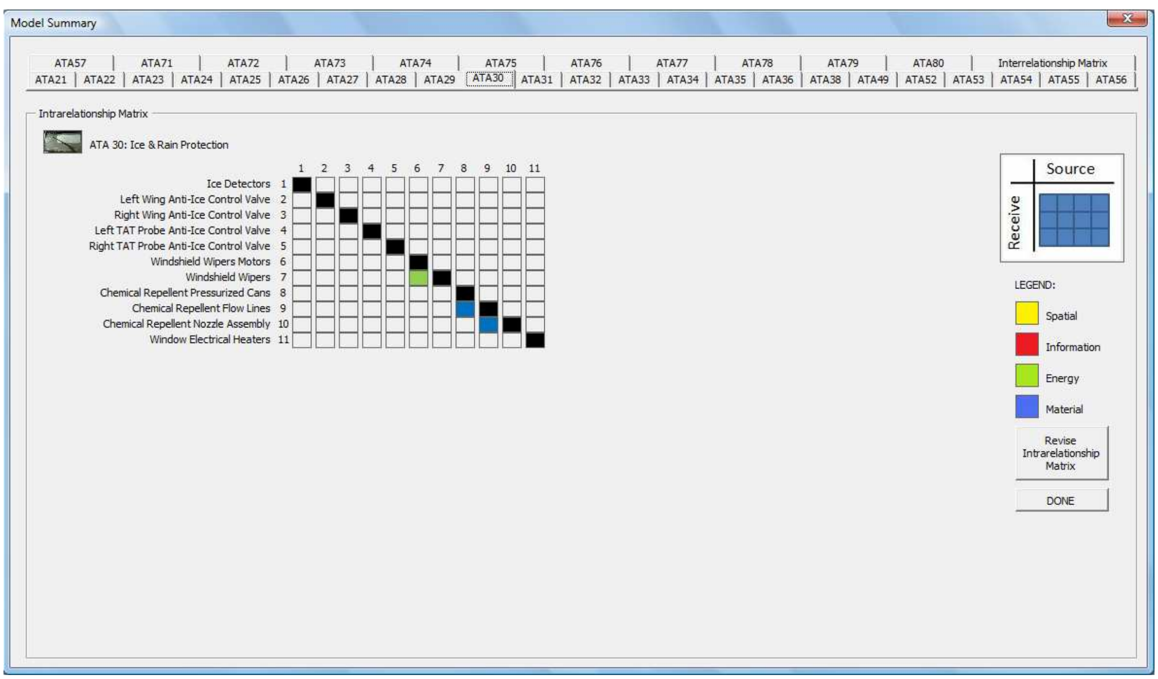

Figure B.10: DSM Model for ATA30 Subsystem of the Notional Aircraft System

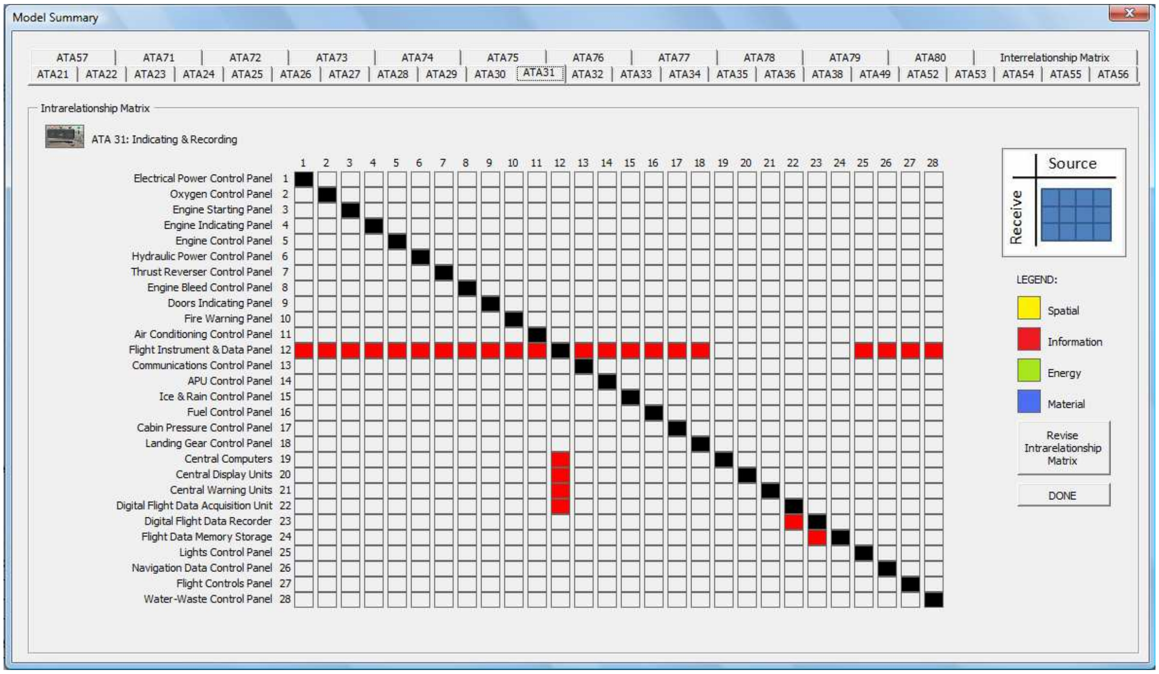

Figure B.11: DSM Model for ATA31 Subsystem of the Notional Aircraft System

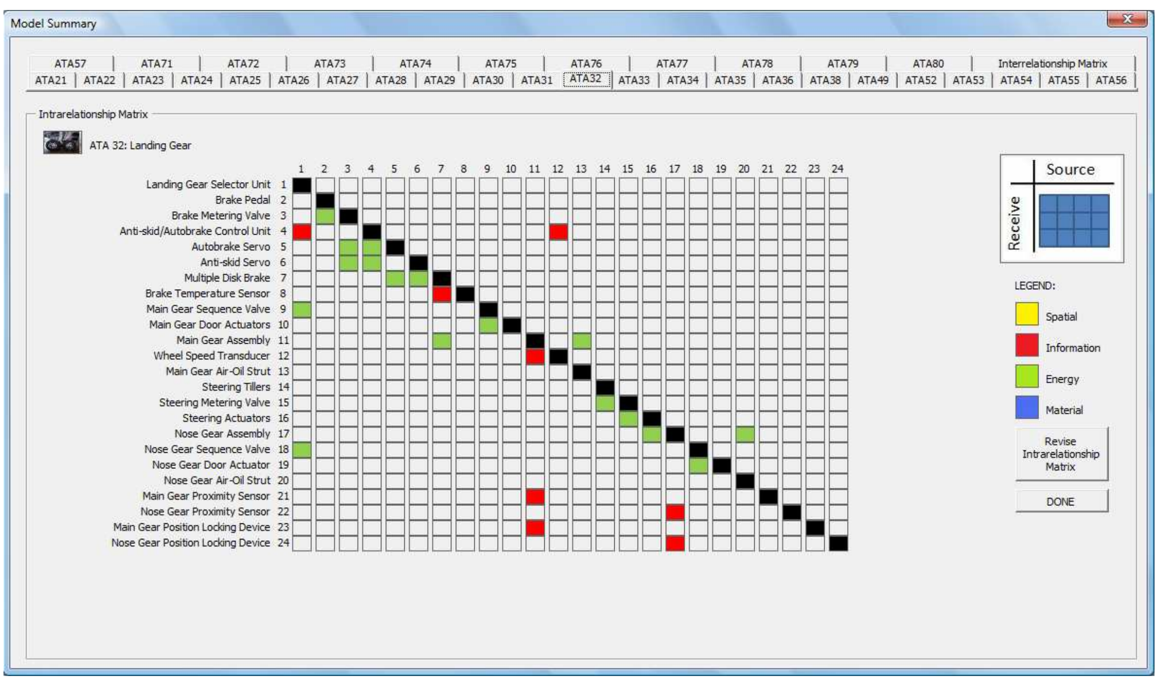

Figure B.12: DSM Model for ATA32 Subsystem of the Notional Aircraft System

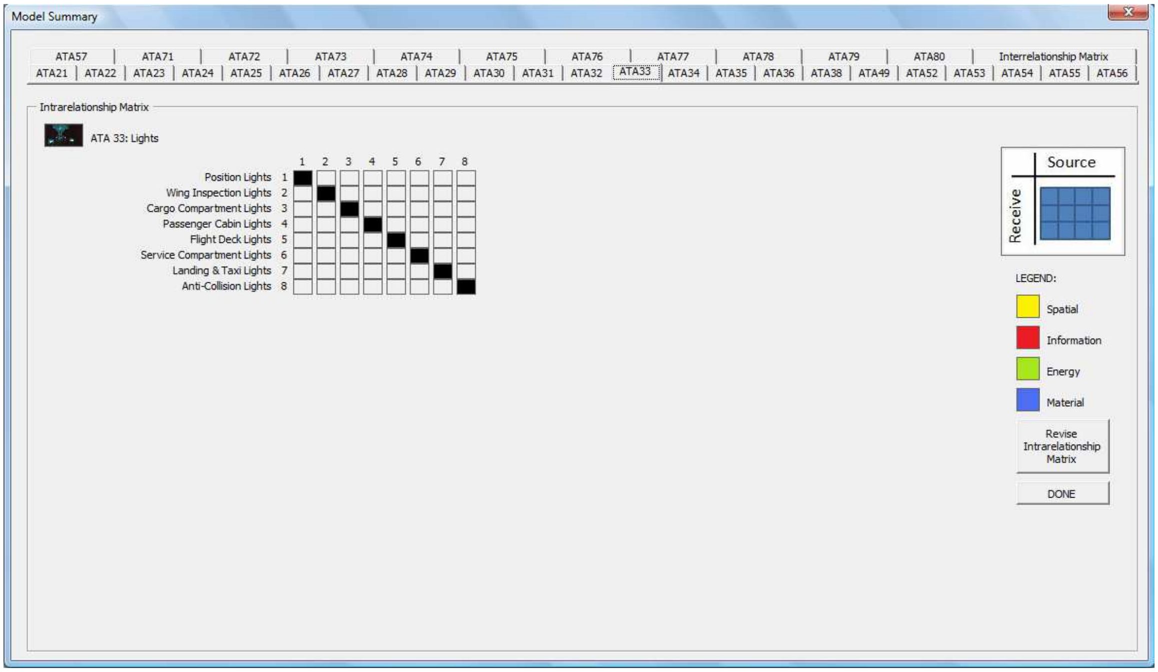

Figure B.13: DSM Model for ATA33 Subsystem of the Notional Aircraft System

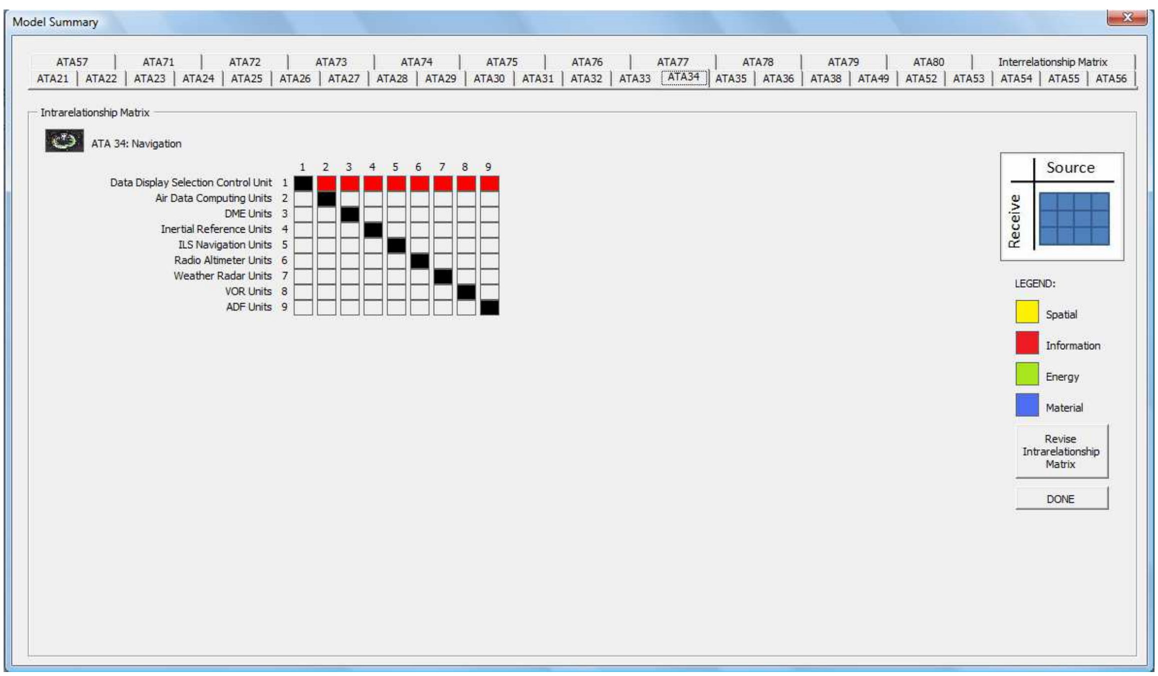

Figure B.14: DSM Model for ATA34 Subsystem of the Notional Aircraft System

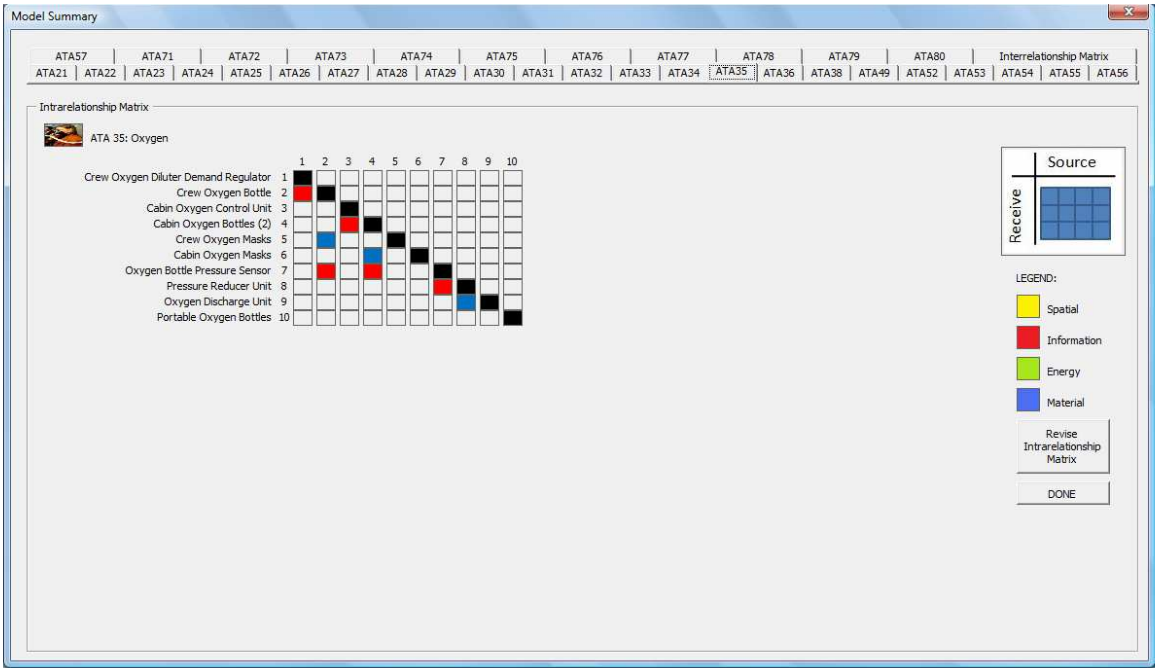

Figure B.15: DSM Model for ATA35 Subsystem of the Notional Aircraft System

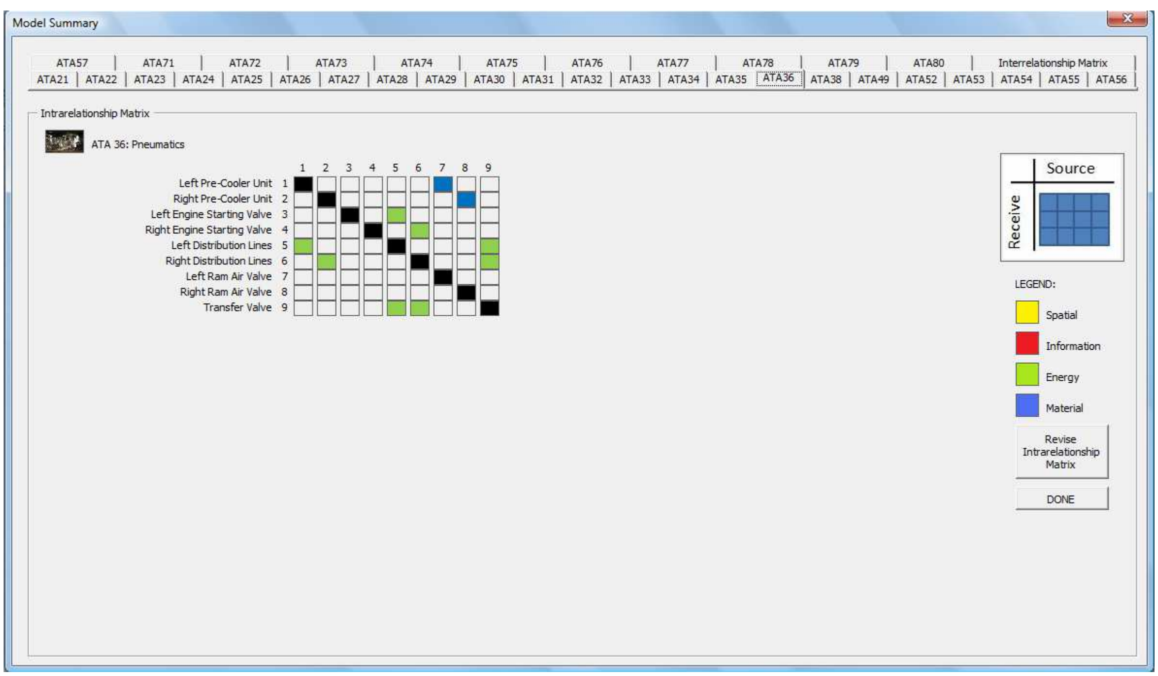

Figure B.16: DSM Model for ATA36 Subsystem of the Notional Aircraft System

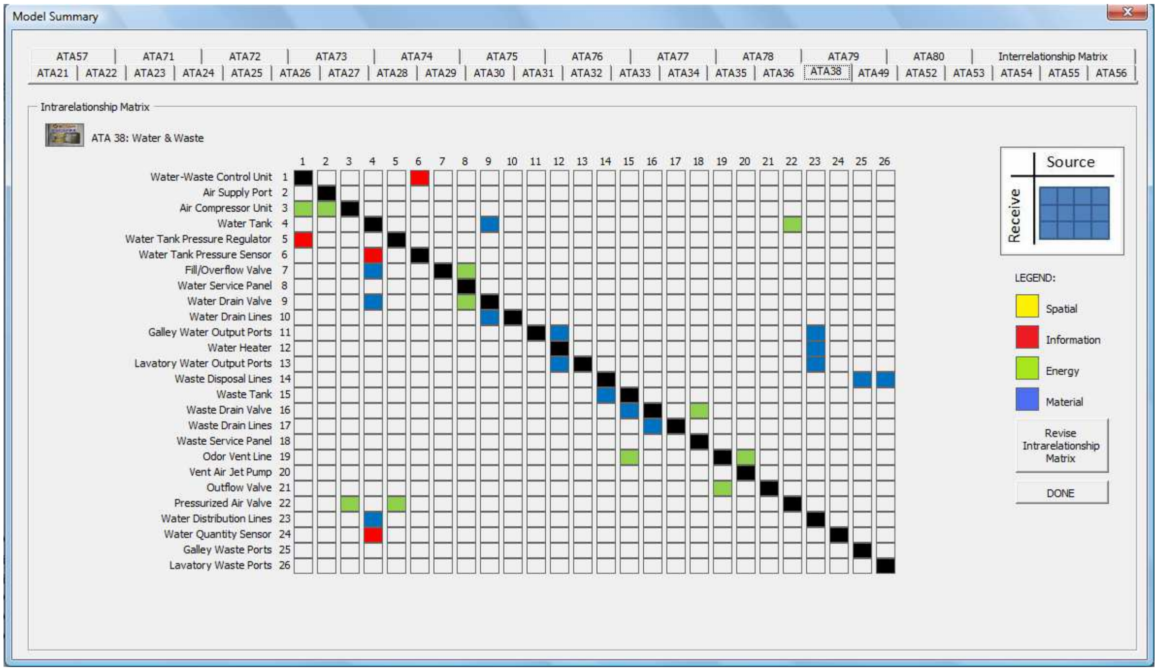

Figure B.17: DSM Model for ATA38 Subsystem of the Notional Aircraft System

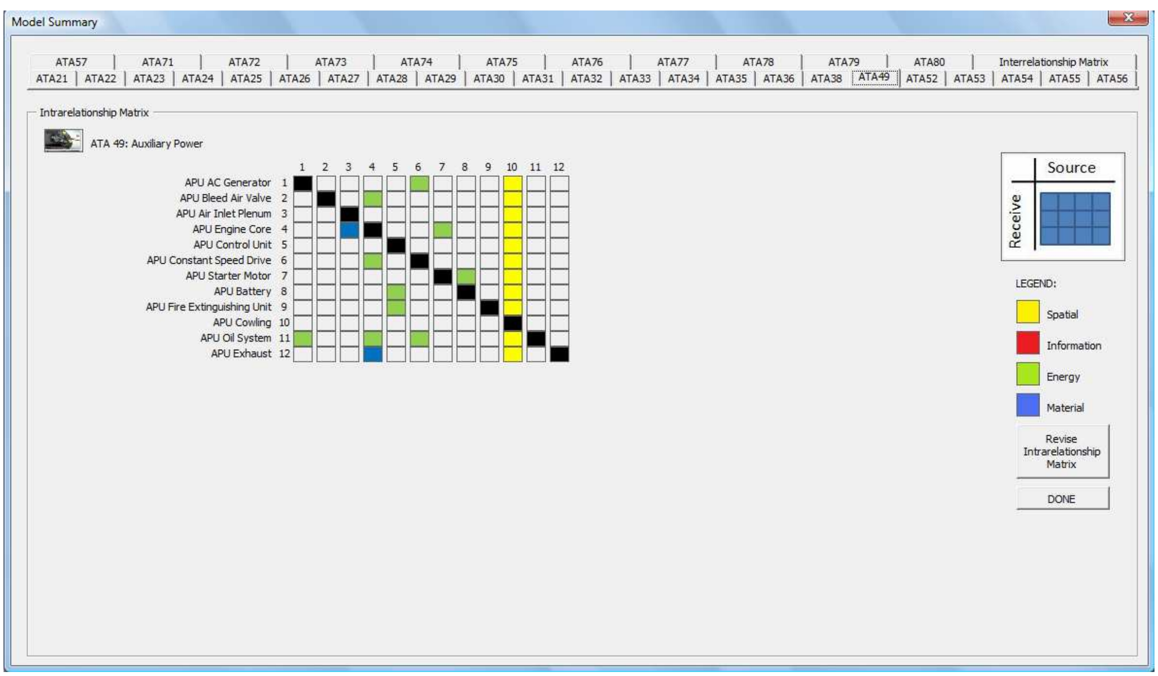

Figure B.18: DSM Model for ATA49 Subsystem of the Notional Aircraft System

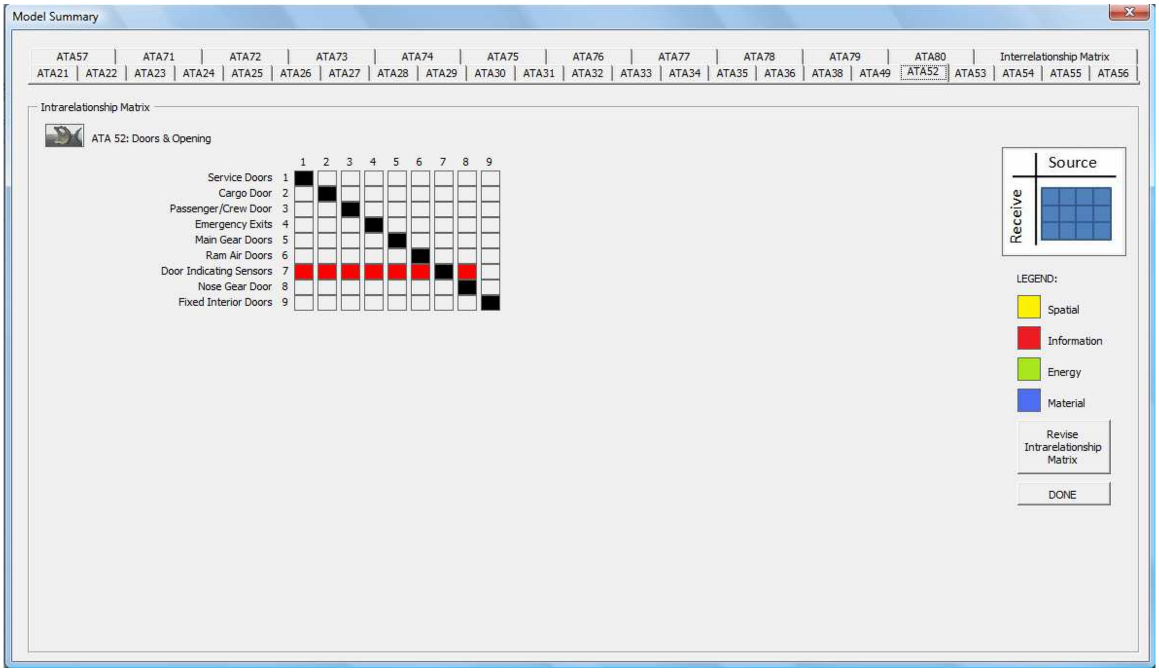

Figure B.19: DSM Model for ATA52 Subsystem of the Notional Aircraft System

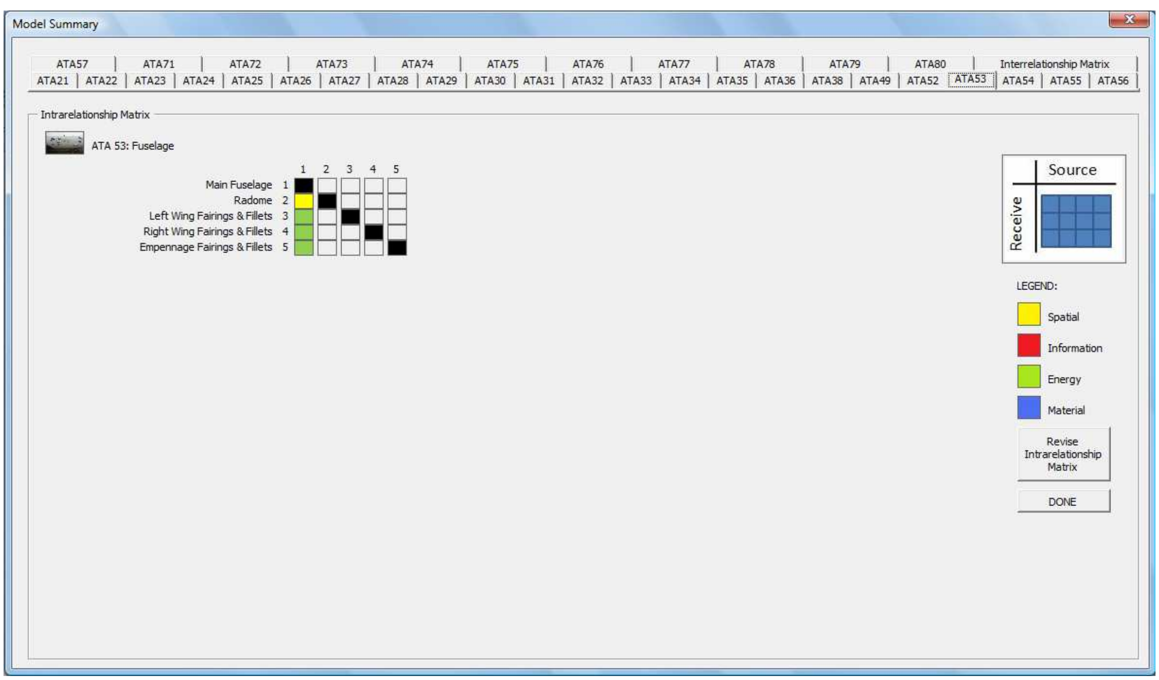

Figure B.20: DSM Model for ATA53 Subsystem of the Notional Aircraft System

Figure B.21: DSM Model for ATA54 Subsystem of the Notional Aircraft System

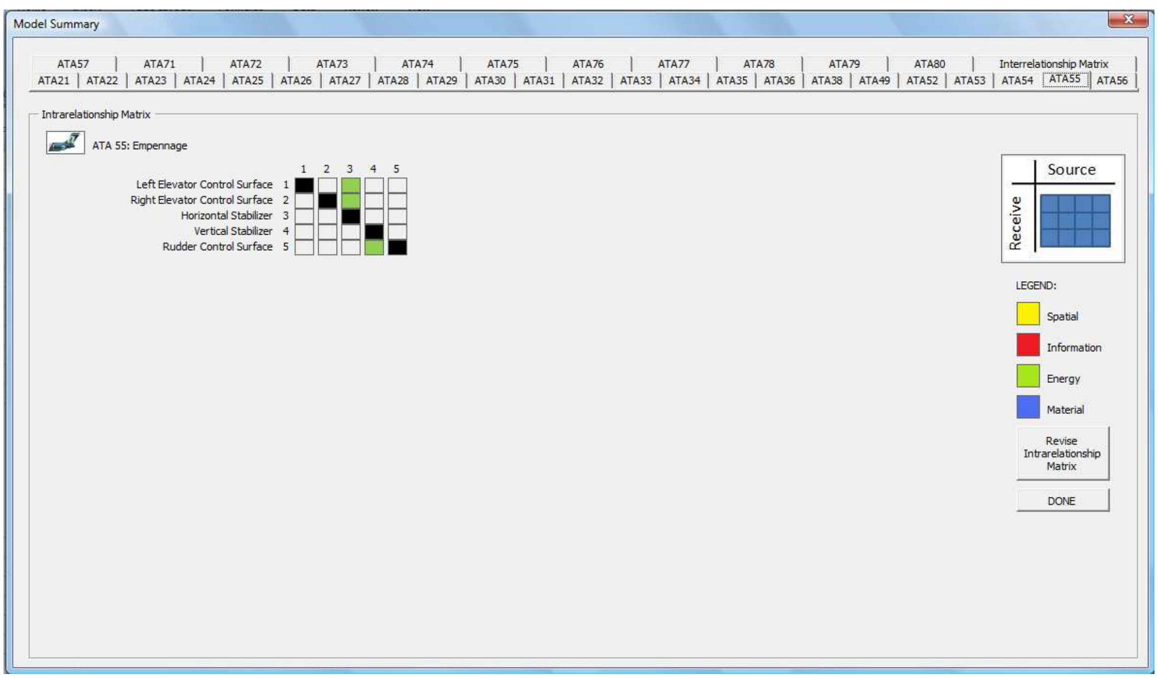

Figure B.22: DSM Model for ATA55 Subsystem of the Notional Aircraft System

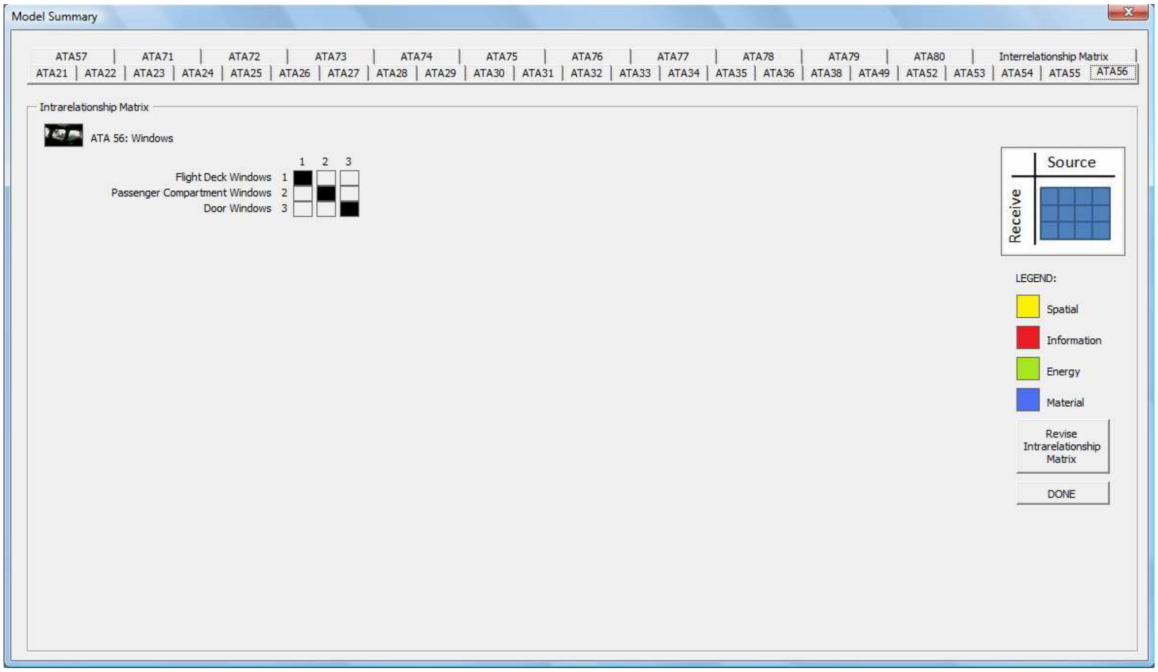

Figure B.23: DSM Model for ATA56 Subsystem of the Notional Aircraft System

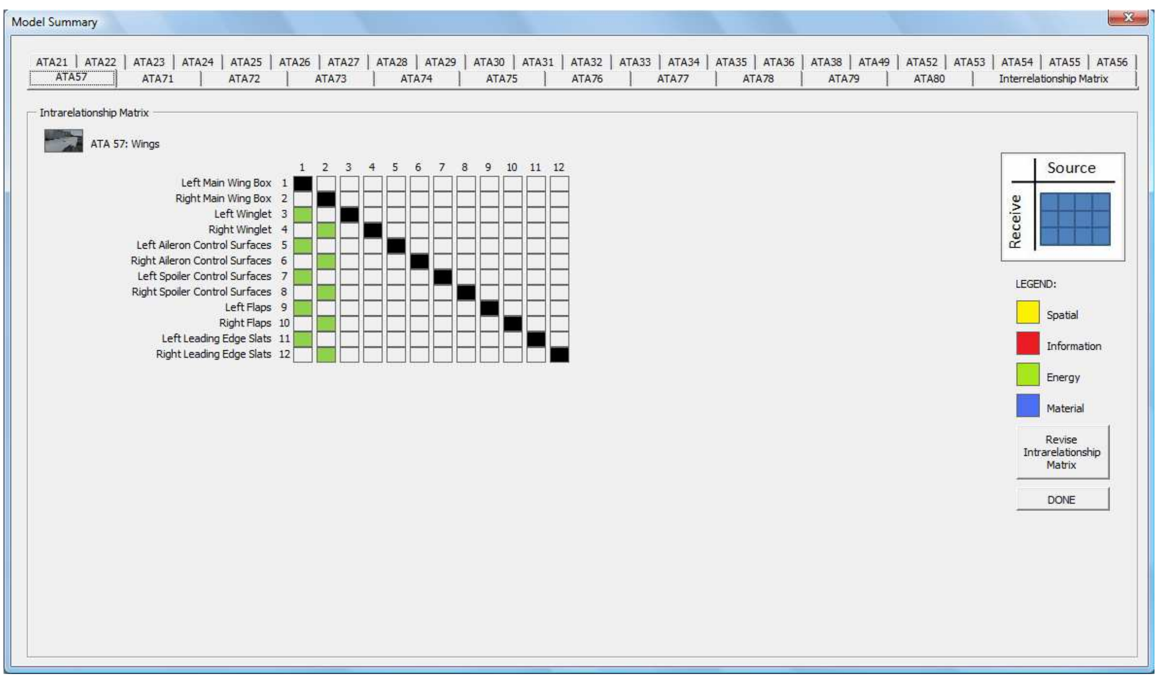

Figure B.24: DSM Model for ATA57 Subsystem of the Notional Aircraft System

Figure B.25: DSM Model for ATA71 Subsystem of the Notional Aircraft System

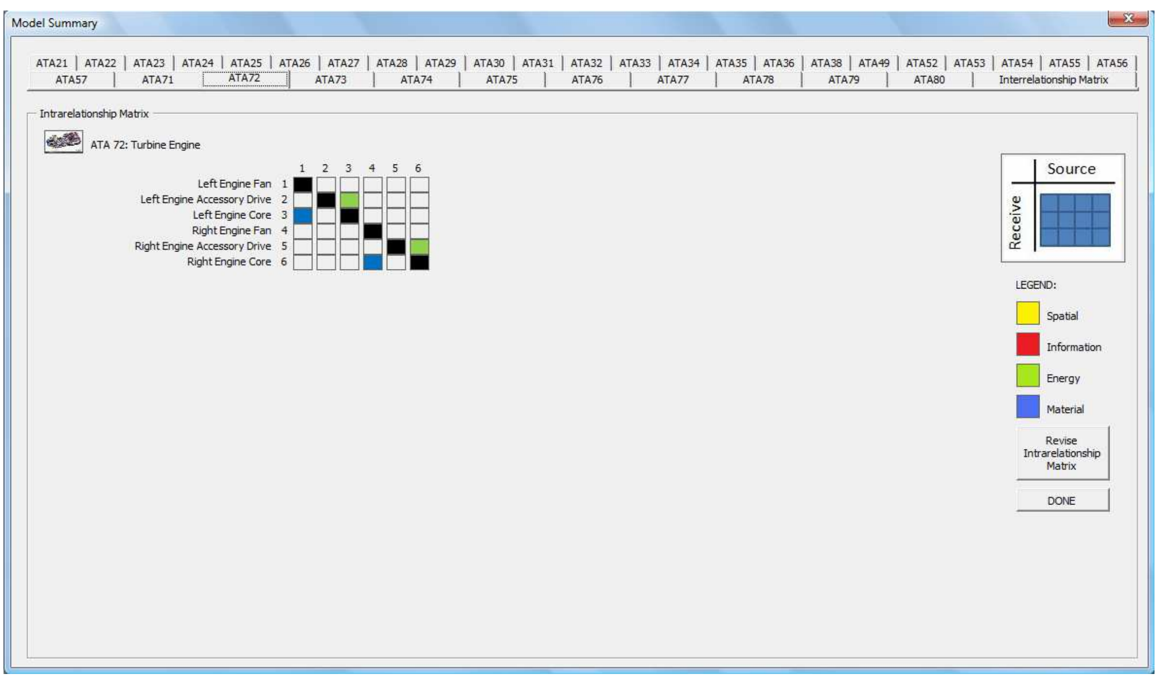

Figure B.26: DSM Model for ATA72 Subsystem of the Notional Aircraft System

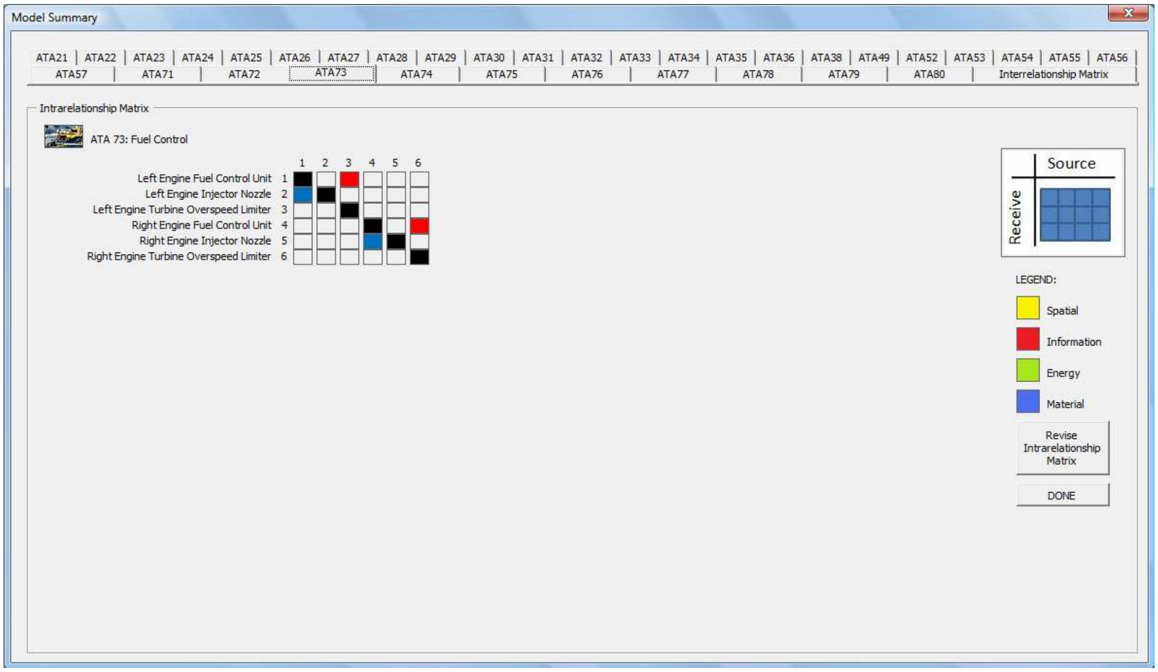

Figure B.27: DSM Model for ATA73 Subsystem of the Notional Aircraft System

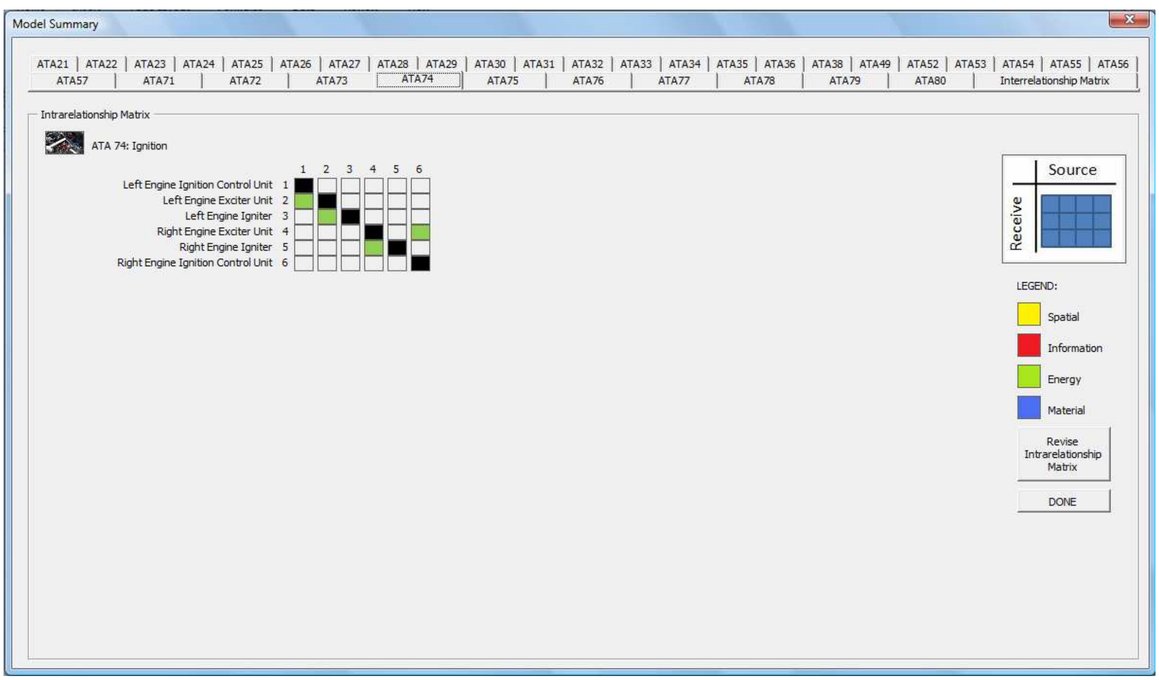

Figure B.28: DSM Model for ATA74 Subsystem of the Notional Aircraft System

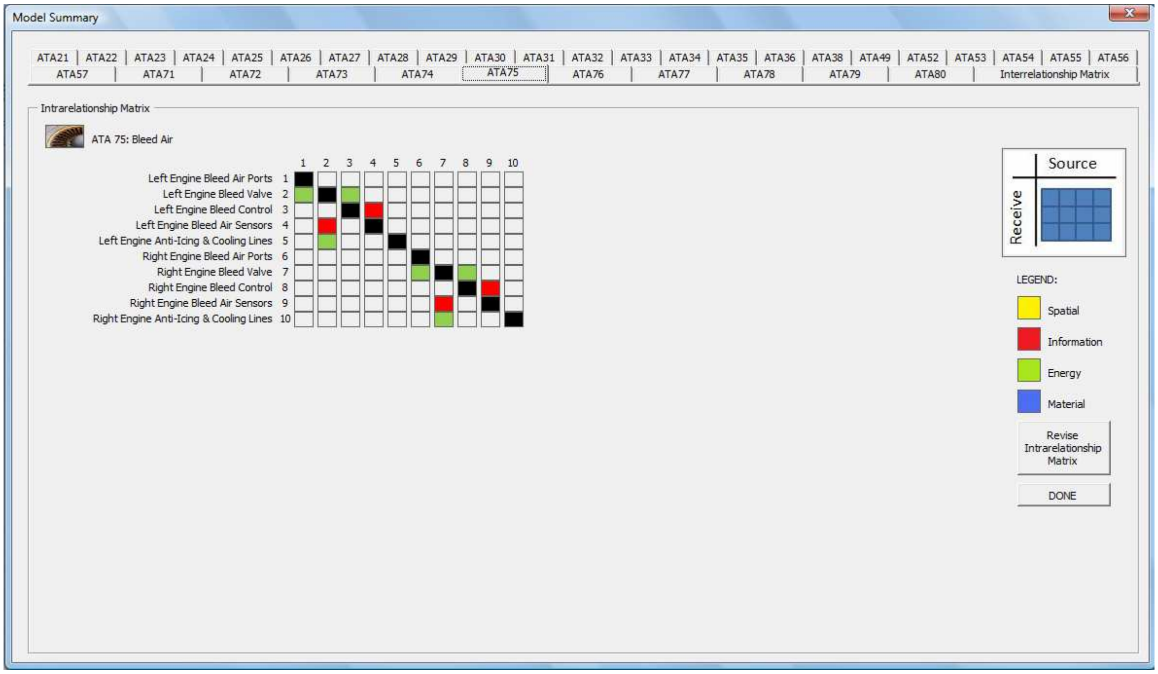

Figure B.29: DSM Model for ATA75 Subsystem of the Notional Aircraft System

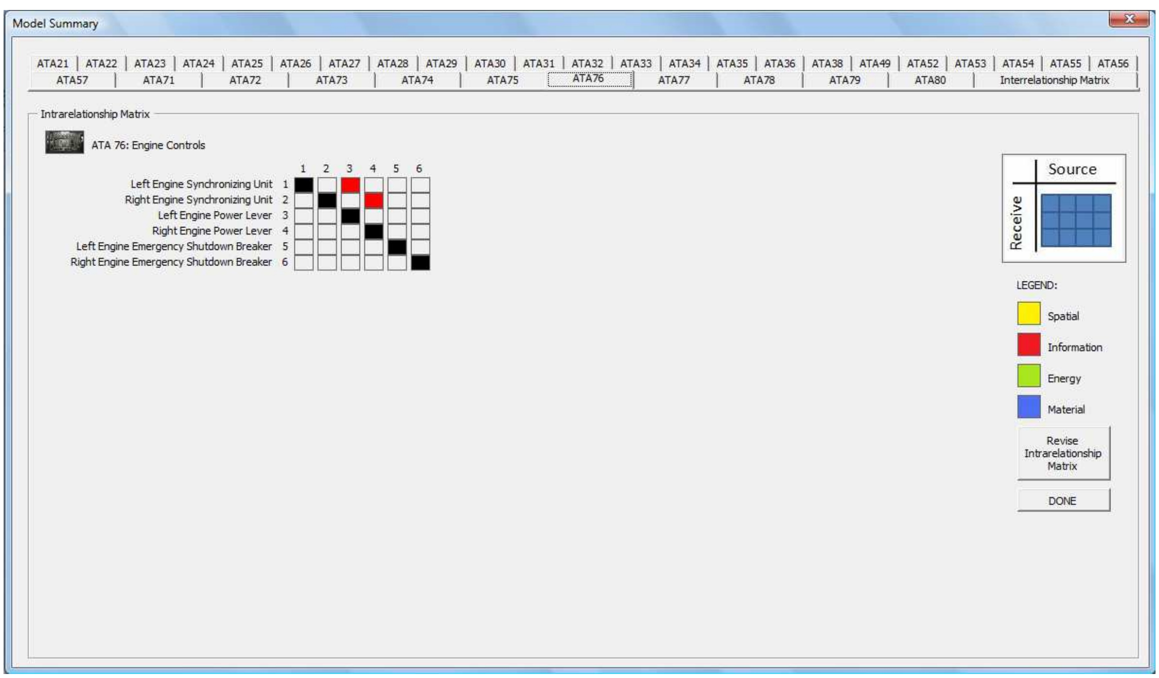

Figure B.30: DSM Model for ATA76 Subsystem of the Notional Aircraft System

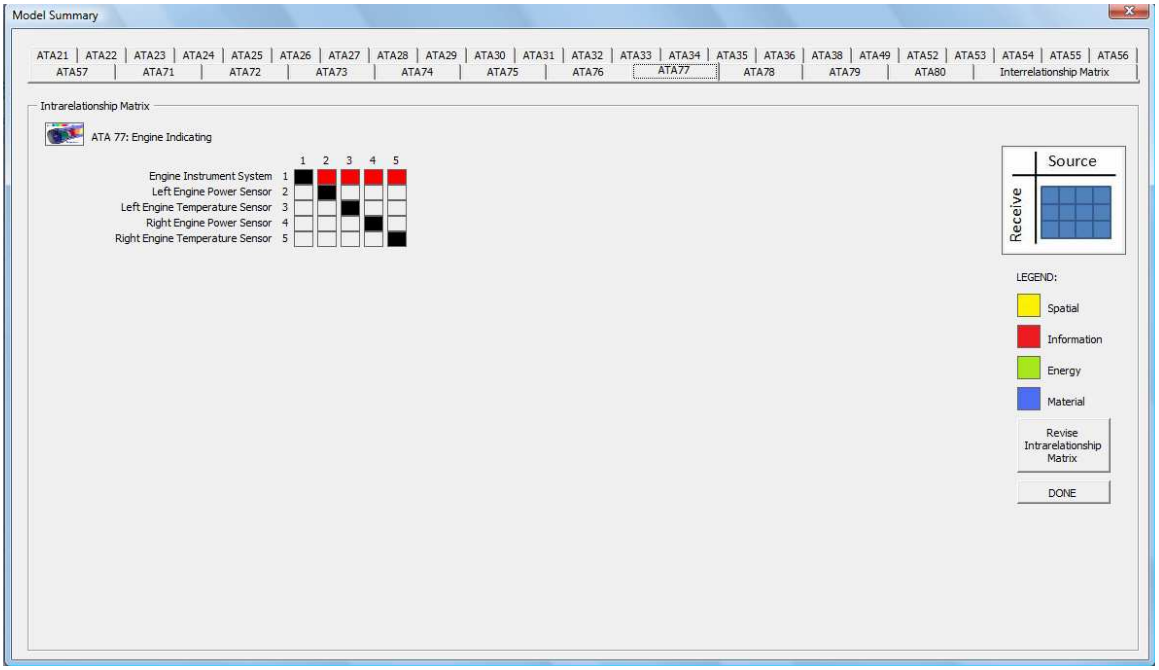

Figure B.31: DSM Model for ATA77 Subsystem of the Notional Aircraft System

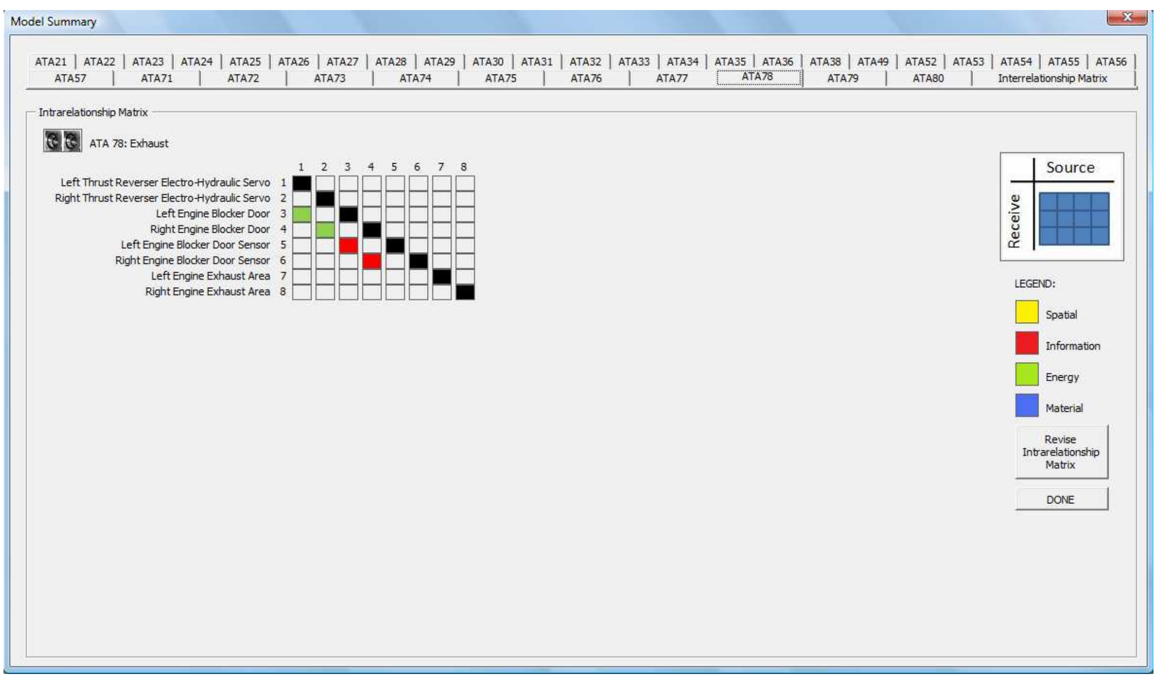

Figure B.32: DSM Model for ATA78 Subsystem of the Notional Aircraft System

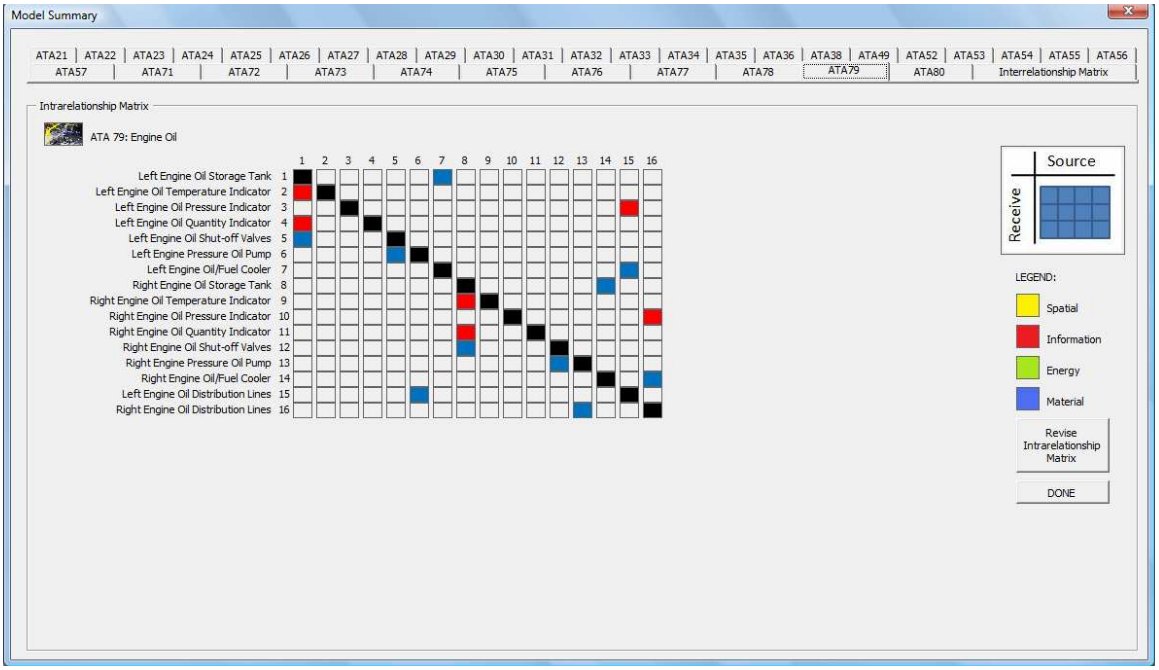

Figure B.33: DSM Model for ATA79 Subsystem of the Notional Aircraft System

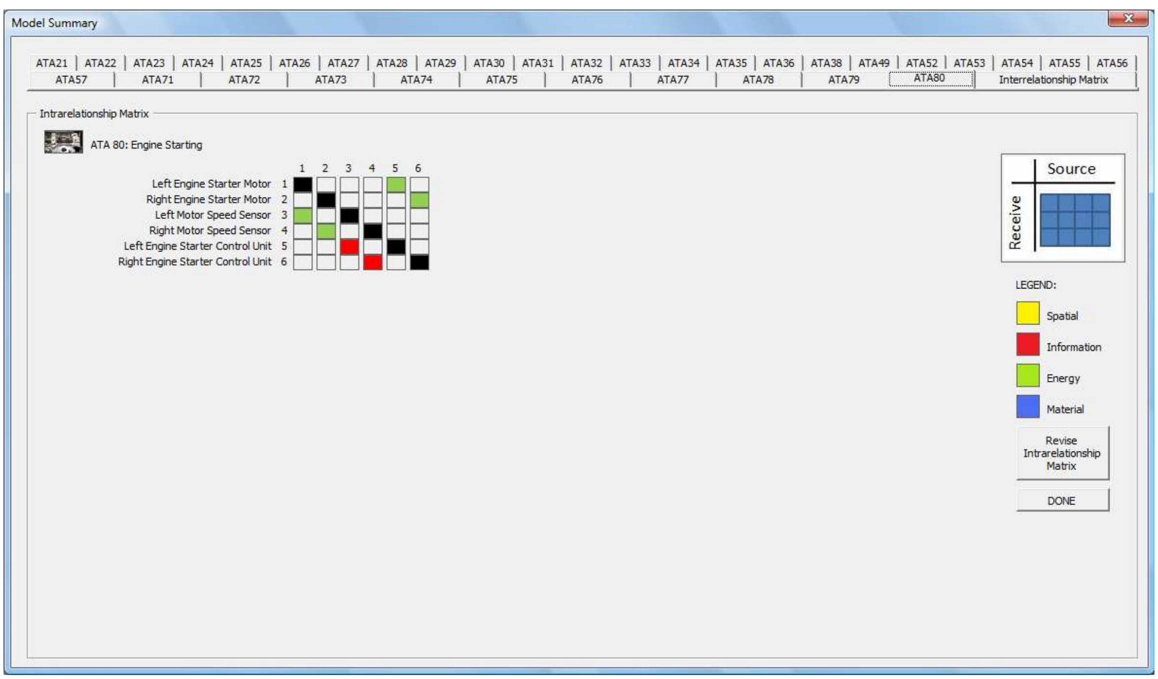

Figure B.34: DSM Model for ATA80 Subsystem of the Notional Aircraft System

APPENDIX C

APPROXIMATED SUBSYSTEM-SYSTEM INTERRELATIONSHIP MODEL FOR CASE STUDY 2

The aircraft subsystem-system interrelationships are approximated through application of Flight Optimization System (FLOPS), which is a public domain synthesis and sizing tool for aircraft system design. For additional information, this FLOPS tool is developed by NASA Langley Research Center and is taken as a fairly robust modeling and simulation code for subsonic commercial transport aircraft types [191]. However, it is good to note that FLOPS is not developed for engineering change analysis and its design parameters are mostly not allocated at the subsystem components level.

For the sample demonstration case study, the interested aircraft system level performance metric to be considered is takeoff gross weight of the notional aircraft system, which is a formulated driving redesign requirement. The input aircraft system model into FLOPS is tailored to design characteristics of Boeing B737-800 aircraft that has been validated by the EDS design team in ASDL. This is taken to be an appropriate model to estimate real performance of the notional aircraft system design since its subsystem models have been mostly constructed based on Boeing B737 design variants.

As can be implied, there are too many subsystem parameters that can be used to construct this relationship. Nevertheless, most design parameters in FLOPS that can be specifically used for a particular aircraft subsystem have been the ones regarding their weights. These available weight correction factors can be used to induce the change effects on the overall aircraft system weight. To further simplify the construction of system-subsystem weight relationship, the weight parameters have been screened down to the ones that are taken to be most likely affected by the initiating design changes. The list of considered subsystem parameters is tabulated in Table C.1.

Table C.1: Considered Subsystem Weight Parameters in FLOPS

Design Parameters	Description [230]
FRNA	Total weight of nacelles and/or air induction system
WPMSC	Weight of miscellaneous propulsion systems such as engine controls, starter and wiring
FRSC	Surface controls weight
WFURN	Furnishings group weight
WHYD	Hydraulics group weight
WAVONC	Avionics group weight
WELEC	Electrical group weight
WFSYS	Weight of fuel system
WAPU	Auxiliary power unit weight
WIN	Instrument group weight
WAC	Air conditioning group weight
WOIL	Engine oil weight

Effects of these 12 design parameters on overall aircraft system gross weight are studied through set-up experimental cases based on design of experiments (DoE) principle. Using MINITAB, fractional factorial experimental design of 128 runs (2^{12-5}) is constructed and each parameter is taken as 2-level with values of 0.75 and 1.25 for the lower and upper level, respectively. Because these parameters act as a weighting factor to the internally computed subsystem weights in FLOPS, it is known that they have a linear relationship with the overall aircraft system. The flight range for the experiments is set to 2950 nmi, which is taken as the desired range capability that will make the notional aircraft system derivative more competitive in comparison to its currently “estimated” 2700 nmi in Table 86. Based on the experimental results, the following simple stepwise regression process is done in MINITAB.

Stepwise Regression: GW versus FRNA, WPMSC, ...

```
Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15


Response is GW on 12 predictors, with N = 128


Step                1          2          3          4          5          6
Constant       166263     163072     160364     157685     155314     152961

WFURN           25317      25317      25317      25317      25317      25317
T-Value         42.54      48.22      54.14      62.88      73.89      93.96
P-Value         0.000      0.000      0.000      0.000      0.000      0.000

WELEC                       3190       3190       3190       3190       3190
T-Value                     6.08       6.82       7.92       9.31      11.84
P-Value                    0.000      0.000      0.000      0.000      0.000

FRSC                                   2708       2708       2708       2708
T-Value                                5.79       6.73       7.90      10.05
P-Value                               0.000      0.000      0.000      0.000

WAC                                               2679       2679       2679
T-Value                                           6.65       7.82       9.94
P-Value                                          0.000      0.000      0.000

FRNA                                                         2371       2371
T-Value                                                      6.92       8.80
P-Value                                                     0.000      0.000

WAVONC                                                                  2353
T-Value                                                                 8.73
P-Value                                                                0.000

S                1683       1485       1323       1139        969        762
R-Sq            93.49      94.97      96.04      97.09      97.91      98.72
R-Sq(adj)       93.44      94.89      95.95      97.00      97.83      98.66
Mallows C-p 1477998.5  1140906.8   898027.9   660285.4   474183.3   290810.1
PRESS       368471906  289009159  231174294  172756394  126115329   78640087
R-Sq(pred)      93.28      94.73      95.79      96.85      97.70      98.57
```

Step	7	8	9	10	11	12
Constant	151185	149489	148301	147484	146691	146487
WFURN	25317.0	25317.0	25317.0	25317.0	25317.0	25317.0
T-Value	116.88	166.49	237.39	333.73	1286.22	4607.34
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
WELEC	3190.3	3190.3	3190.3	3190.3	3190.3	3190.3
T-Value	14.73	20.98	29.92	42.05	162.08	580.60
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
FRSC	2708.1	2708.1	2708.1	2708.1	2708.1	2708.1
T-Value	12.50	17.81	25.39	35.70	137.58	492.83
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
WAC	2679.3	2679.3	2679.3	2679.3	2679.3	2679.3
T-Value	12.37	17.62	25.12	35.32	136.12	487.59
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
FRNA	2370.5	2370.5	2370.5	2370.5	2370.5	2370.5
T-Value	10.94	15.59	22.23	31.25	120.43	431.40
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
WAVONC	2353.1	2353.1	2353.1	2353.1	2353.1	2353.1
T-Value	10.86	15.47	22.06	31.02	119.55	428.22
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
WHYD	1775.9	1775.9	1775.9	1775.9	1775.9	1775.9
T-Value	8.20	11.68	16.65	23.41	90.22	323.19
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
WAPU		1696.7	1696.7	1696.7	1696.7	1696.7
T-Value		11.16	15.91	22.37	86.20	308.78
P-Value		0.000	0.000	0.000	0.000	0.000
WFSYS			1187.2	1187.2	1187.2	1187.2
T-Value			11.13	15.65	60.32	216.05
P-Value			0.000	0.000	0.000	0.000
WPMSC				817.8	817.8	817.8
T-Value				10.78	41.55	148.82
P-Value				0.000	0.000	0.000
WIN					792.7	792.7
T-Value					40.27	144.26
P-Value					0.000	0.000
WOIL						203.6
T-Value						37.06
P-Value						0.000
S	613	430	302	215	55.7	15.5
R-Sq	99.18	99.60	99.80	99.90	99.99	100.00
R-Sq(adj)	99.13	99.57	99.79	99.89	99.99	100.00
Mallows C-p	186359.4	91017.5	44340.1	22193.9	1384.4	13.0
PRESS	51248934	25467751	12633526	6447126	437769	34414.2
R-Sq(pred)	99.07	99.54	99.77	99.88	99.99	100.00

Based on this, the subsystem-system weight relationship is given as follows:

$$Gross\,Weight\,(lb) = 146487 + 25317WFURN + 3190.3WELEC + 2708.1\,FRSC$$
$$+ 2679.3WAC + 2370.5FRNA + 2353.1WAVONC + 1775.9WHYD + 1696.7WAPU$$
$$+ 1187.2WFSYS + 817.8WPMSC + 792.7WIN + 203.6WOIL$$

To further check for the goodness of this derived relationship, 50 random cases have been generated and run in FLOPS. The resultant residual histogram of the actual vs. predicted values obtained from the random cases is presented in Figure C.1 below.

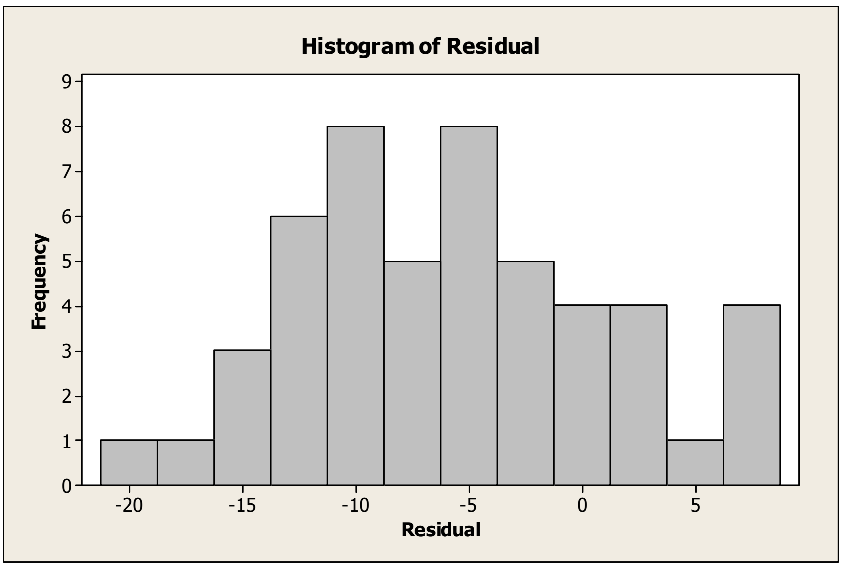

Figure C.1: Residual Histogram for the Random Cases

As can be observed from Figure C.1, the residual histogram effectively follows a normal distribution, justifying the goodness of the derived relationship. The residuals magnitude is also rather insignificant against the high gross weight value. On the whole, it is taken that this estimated system-subsystem weight relationship can adequately capture the real relationship based on its measure of goodness presented above.

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